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LIMITED EVALUATION OF AN 802.11b AIR-TO-GROUND WIRELESS DATALINK (PROJECT "HAVE HALO")

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This Technical Information Memorandum (AFFTC-TIM-06-03, Limited Evaluation of an 802.11b Wireless Datalink, Project "HAVE HALO") was prepared and submitted under Job Order Number M06C0400 by the HAVE HALO test team, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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14. ABSTRACT
This report presents the results of the limited evaluation of an 802.11b wireless air-to-ground datalink between a ground station and a C-12C aircraft. Testing occurred between 10 April and 2 May 2006. This test program demonstrated the 802.11b wireless datalink reception range when transmitting at 4 Watts effective isotropic radiated power. The test team also demonstrated the utility of high resolution imagery and streaming video transmitted across the datalink. The test team identified deficiencies in operating system employment during high resolution imagery and streaming video transmissions.

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PREFACE

The HAVE HALO test team would like to extend a special note of thanks to Mr. Chris Howell from the Tybrin Corporation. We are indebted to Mr. Howell for his on-site engineering expertise during ground and flight testing. Mr. Howell volunteered his time to provide technical guidance on equipment and data collection software selection and training. He also was on hand during all ground and flight testing to provide technical guidance, ensuring the successful completion of the test program.

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EXECUTIVE SUMMARY

The US Air Force Test Pilot School (TPS) Class 05B HAVE HALO Test Management Project group accomplished flight testing of an 802.11b air-to-ground wireless datalink between a C-12C and a ground station. This test project was conducted at the request of Headquarters, Air Combat Command (HQ/ACC/A8G). All testing was accomplished under TPS Job Order Number M060400. A total of 17.6 hours were flown on seven flight test sorties in the R-2508 complex from 10 April to 2 May 2006.

An Air Force Flight Test Center, 412th Test Wing, Raytheon C-12C Huron twin-engine turboprop transport aircraft, serial number 73-1215 was the test aircraft. The system under test consisted of S band antennas on the aircraft and the ground station, radio frequency signal amplifiers for the antennas, an electronic display unit for the pilots, a laptop PC connected to the aircraft station, a tablet PC connected to the ground station, and two Cisco® Aironet 1200 Wireless access points connected to the ground and aircraft amplifiers.

Flight test support hardware was provided by the TPS Special Instrumentation branch. The 412th Test Wing, Range Support Division (412 TW/ENR) provided a GPS Aided Inertial Reference System with an Embedded GPS Inertial Navigation System for aircraft #73-1215.

The test team successfully performed a limited evaluation of an 802.11b wireless air-to-ground datalink. This test program demonstrated the 802.11b wireless datalink reception range when transmitting at 4 Watts effective isotropic radiated power. The test program demonstrated the utility of transmitting high resolution imagery and streaming video across the datalink within specific signal-to-noise ranges. The test team also evaluated the utility of high resolution imagery and streaming video transmitted across the datalink. The test configuration identified deficiencies in operating system employment during high resolution imagery and streaming video transmissions. However, the system demonstrated the bandwidth and ground distance/altitude capabilities of the 802.11b wireless network.

The HAVE HALO 802.11b wireless air-to-ground datalink performance was satisfactory in its tested configuration for transmitting high resolution imagery. However, it was not adequate in its tested configuration to provide reliable time-critical targeting streaming video. The datalink reception envelope provided operationally useful data ranges, with low data rate connections established between the aircraft and ground station at ground distances greater than 15 nm for the tested altitudes.

Figure I-1: HAVE HALO Aircraft Ground Testing

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INTRODUCTION

Background

The HAVE HALO test program provided data to Lockheed Martin, which would determine the suitability of using an 802.11b wireless datalink to test their Mission Battle Management System (MBMS). The MBMS would provide time based task management for Integrated Warfare applications and would require reliable, high speed datalinks to transmit time critical tactical information. The HAVE HALO test effort was a proof of concept for follow-on testing of 802.11b wireless networks between multiple aircraft and ground stations.

The HAVE HALO test team from the USAF Test Pilot School (TPS) at Edwards AFB, CA performed ground and flight testing of an 802.11b wireless datalink between a C-12C aircraft and a ground station. The test team determined the reception range of the wireless datalink transmitting at 4 Watts effective isotropic radiated power (EIRP). The test team also determined the in-flight datalink performance statistics at different negotiated data rates, altitude/ground ranges and bank angles while evaluating the utility of high resolution imagery and streaming video transmitted across the datalink and displayed on an electronic display unit.

The HAVE HALO Test Management Project (TMP) was conducted at the request of Headquarters, Air Combat Command (HQ/ACC/A8G). The Responsible Test Organization for this project was the 412th Test Wing. The USAF TPS HAVE HALO Test Team acted as the executing organization as directed by the Commandant, USAF TPS. All testing was accomplished under TPS Job Order Number M060400. A total of 17.6 hours of flight test were flown on seven sorties using a C-12C aircraft and a deployed aircraft in the R-2515 complex from 10 April to 2 May 2006.

Program Chronology

Aircraft modifications were completed on 31 March 2006. Flight testing was conducted between 10 April 2006 and 2 May 2006.

Test Item Description

The system under test (SUT) consisted of airborne and ground station antennas with amplifiers, an IBM® ThinkPad PC running Windows® XP Professional Edition Service Pack 2, datalink performance collection software for the ground and aerial nodes, two Itronix® DuoTouch tablet PCs for the electronic display units, two Cisco® Aironet 1200 wireless access points, and two GARMIN® GPS units for datalink synchronization. The airborne and ground datalink transmitters transmitted at 4 Watts EIRP over the antennas at a frequency between 2.4 GHz and 2.5 GHz. The airborne GPS receiver was spliced into a GPS antenna mounted on the tail of the C-12C. Table 1 lists the components that were used during testing.

The Itronix® electronic display unit and the IBM® ThinkPad PC at the ground and aircraft stations used specific performance statistics software packages to collect data. To characterize the data reception envelope, the NetStumbler (reference 1) package recorded signal-to-noise ratio and negotiated data rate between the aircraft and the ground station. In order to collect the throughput, utilization, and packet statistics, Microsoft Windows® XP Performance Monitor was configured to record datalink parameters at the ground station.

Table 1: Components of the SUT for the HAVE HALO TMP

Component	Model	Manufacturer
Aerial Blade Antenna	6030-2	Haigh-Farr
Ground Antenna	6030-2	Haigh-Farr
10-20 dB Attenuator	768-20	Narda
5 Watt Amplifier	HA2405GTI-NF	Hyperlink Technologies
GPS Receiver	GPSMAP 296	GARMIN®
Duo Touch Tablet PC	IX325	Itronix®
IBM® ThinkPad	T-40	IBM®
Wireless Access Point	AIR-AP1220B	Cisco®
Network Card	ORiNOCO 8470-FC	Proxim®

Test Team

The test team consisted of five members of TPS Class 05B at the USAF Test Pilot School. Two team members were pilots and three team members were flight test engineers. All team members participated in the flight testing and ground station operations.

Test Objectives

The overall test objective was to perform a limited evaluation of an 802.11b air-to-ground wireless datalink. The evaluation was broken into three specific objectives:

1. Determine the datalink reception envelope
2. Determine the datalink performance characteristics
3. Evaluate the in-flight operational utility of an electronic display unit

All test objectives were met.

Limitations

There were no limitations.

TEST AND EVALUATION

General

The overall test objective was to perform a limited evaluation of an 802.11b air-to-ground wireless datalink. The evaluation was broken into three objectives: determine the datalink reception envelope, determine the datalink performance characteristics, and evaluate the in-flight operational utility of an electronic display unit using the datalink for high resolution imagery and streaming video data transmissions. Approximately 17 hours of ground test to verify system functionality were accomplished prior to flight test. A total 17.6 hours of flight time on seven C-12C flights with a deployed ground station were flown in the R-2515 complex from 10 April 2006 to 2 May 2006 to accomplish the test objectives.

Datalink Reception Envelope

This test objective was to determine the datalink reception envelope between the aircraft and ground station.

Procedures

The wireless network connection interface was activated on the aircraft, enabling 802.11b wireless devices to be observed by the aircraft. The wireless connection interface was also activated at the ground station. The Network Stumbler software running on the IBM® ThinkPad on the aircraft recorded wireless devices detected by the Proxim® card connected to the amplifier and external S band antenna. At an interval of once every second, the Network Stumbler software recorded the signal-to-noise ratio (SNR) of all detected 802.11b wireless devices. The software determined the negotiated data rate of the 802.11b wireless datalink based upon the SNR of the ground station signal detected at the aircraft.

The 802.11b standard defined four discrete negotiated data rates for the wireless datalink. Table 2 provides the SNRs corresponding to the specific data rates. The ground station wireless access point transmitted at 4 Watts effective isotropic radiated power. If the negotiated data rate was 5.5 megabit per second (Mbps) or 11 Mbps, the aircraft was considered in the “High Data Rate” connection area, and if the negotiated data rate was 2 Mbps or 1 Mbps it was considered to be in the “Low Data Rate” connection area. If the SNR dropped to zero, then there was no connection between the aircraft and ground station. This was defined as the “No Connection” area.

Table 2: Network Stumbler SNR to Negotiated Data Rate Conversion

802.11b Negotiated Data Rate	SNR	Data Rate
11 Mbps	>16	High
5.5 Mbps	8-15	High
2 Mbps	4-7	Low
1 Mbps	1-3	Low

Ground testing was performed on 27-29 March 2006 to ensure the ground and aircraft nodes could establish a wireless network connection. To determine the ground distance range during flight testing, the test team executed Flight Profile One of appendix C. The Network Stumbler software provided real-time SNR for the ground station and other 802.11b wireless devices. Outbound runs were terminated after the aircraft lost connection with the ground station for 15 seconds. For inbound runs, the aircraft continued flying away from the ground station for 1-2 minutes before setting up for the inbound run. This ensured that the inbound data run would begin with no connection between the aircraft and ground station. For all flight profile maneuvers, the ground antenna was oriented on a 254 deg magnetic heading (270 deg true) to standardize the runs and mitigate any possible antenna nulls which were investigated with flight profile two.

The Haigh-Farr manufacturer laboratory specifications indicated that the antennas used during testing were isotropic throughout the hemisphere of transmission. Flight profile two of appendix C was executed to determine the antenna azimuth profile in the operational environment. Flight profile one verified that the antenna exhibited symmetric radiation patterns around the axis, so 180 deg of testing was accomplished for flight profile two. Network Stumbler was again used to collect SNR and negotiated data rate data with respect to the aircraft and ground station.

During post-flight data analysis, the SNR along the flight path was used to determine the negotiated data rate based on the ground distance from the aircraft to the ground station. The specific negotiated data rate boundaries were determined by examining the Network Stumbler output file as the SNR decreased for outbound runs and increased for inbound runs. The ground distance was determined by calculating the distance between the aircraft position recorded from the GARMIN® GPSMAP 296 and the surveyed ground station location. The ground station deployment location was identical for all test points flown during the test program.

Aircraft configuration for all test points flown for Flight Profiles One and Two was cruise configuration (gear up, flaps up). The propeller speed was 1700 rpm, a standard cruise propeller setting. The maneuvers were flown in the data band of 180 ± 5 KIAS and 5,000, 10,000, 15,000 and 20,000 feet AGL ± 100 feet.

Results

The ground distances for the 802.11b negotiated data rates were determined for each altitude and are summarized in figures 1 and 2. Figure 1 summarizes the ground range for the transition from high to low data rates and figure 2 summarizes the ground range for the transition from low data rate to no connection. The no connection range was defined as 15 seconds of no signal between the aircraft and the ground station. The 95 percent confidence intervals are also provided for each altitude and data rate boundary based on the data collected. The specific data ranges for each run are summarized in tables D-1, D-2, D-3 and D-4 of appendix D, and the average data range with the associated 95 percent confidence intervals are shown in figures D-1, D-2, D-3 and D-4. To ensure there was no disparity between the inbound and outbound runs, the average data rates of both were separately analyzed. Figures D-5, D-6, D-7 and D-8 show the average data range with the associated 95 percent confidence interval for the inbound and outbound runs for each negotiated data rate. For all negotiated data rates and altitudes the 95 percent confidence intervals overlap. Based on the confidence interval overlap shown in the figures, the final data analysis did not differentiate between inbound and outbound runs.

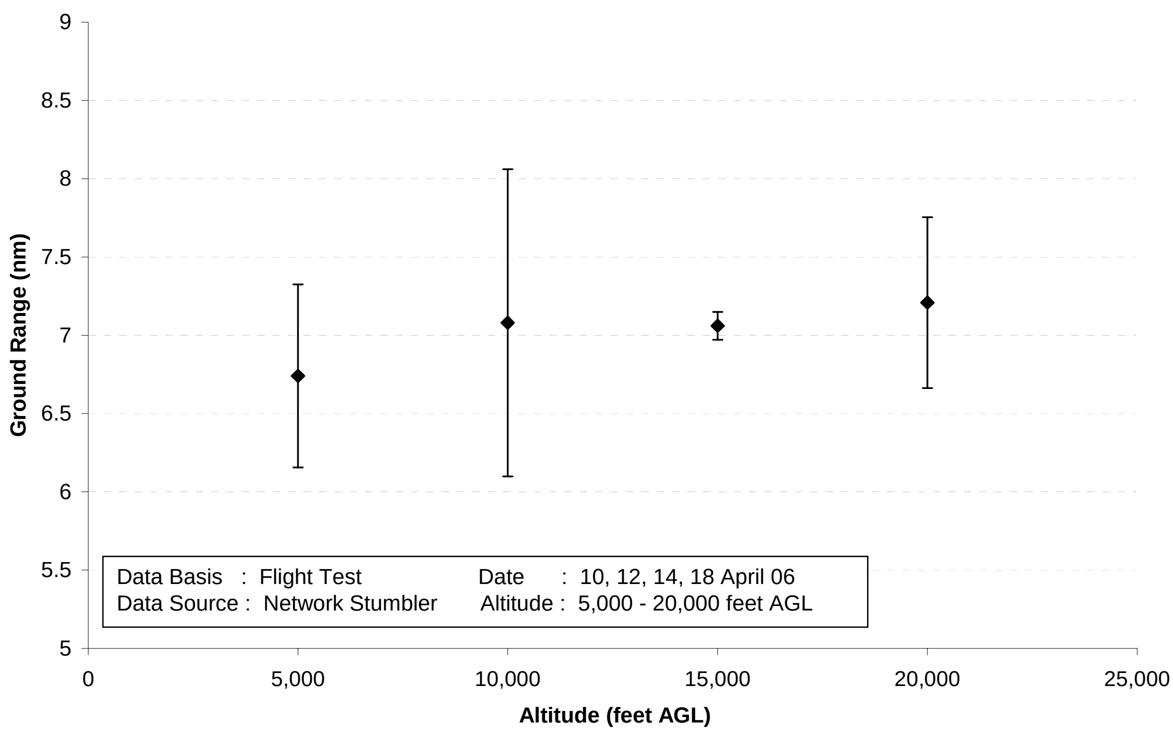

Figure 1: High Data Rate Reception Boundary with 95 Percent Confidence

The average ground range transition from high data rate to low data rate as shown in figure 1 was consistent between the four altitudes, differing by a maximum of 0.5 nm between 5,000 and 20,000 feet AGL. For 5,000, 15,000 and 20,000 feet AGL, the data were very consistent, resulting in low 95 percent confidence differences. The 10,000 feet AGL average range was consistent with the other altitudes, but had a higher 95 percent confidence difference. Even at 10,000 feet AGL, the 95 percent confidence difference from high data rate to low data rate was low, at approximately ±1 nm.

Since the 802.11b wireless network negotiated the data rate based on discrete SNRs, the boundaries between the data rates were an important operational consideration. For example, if the aircraft detected a SNR of 16, the negotiated data rate was 11 Mbps. If the SNR dropped by one to 15, the negotiated data rate dropped to 5.5 Mbps. The consistency of the flight test data corresponded to a well-defined boundary between the high and low data rate ranges. A well defined boundary between the high and low data rates represented an important operational benefit, since the data rates dropped by more than 50 percent (from 5.5 Mbps to 2 Mbps) when the SNR decreased from eight to seven.

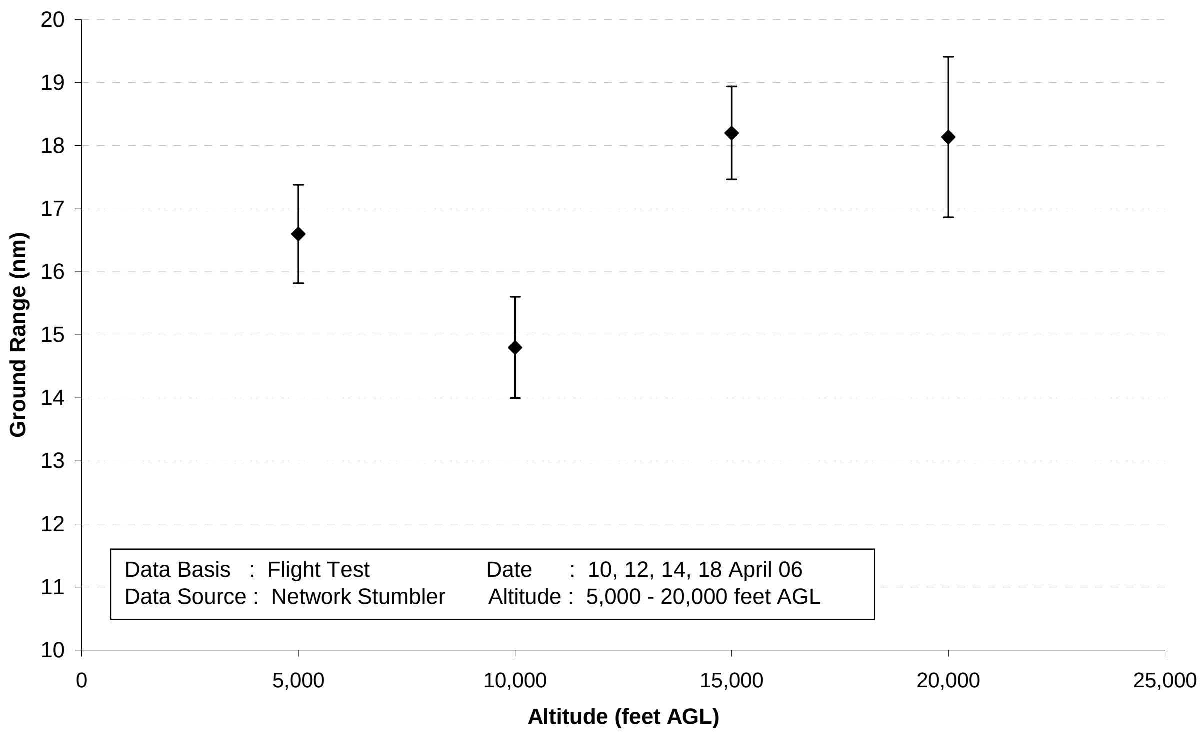

Figure 2: Low Data Rate Reception Boundary with 95 Percent Confidence

The average ground range transition from low data rate to no connection was not as consistent between the four altitudes as the range boundary between high to low data rate. The average range was consistent between 15 and 20,000 feet AGL. For 5,000 and 10,000 feet AGL, the average range dropped by approximately 1.5 and 3 nm respectively. The 95 percent confidence differences were consistent for each negotiated data rate, resulting in a high confidence that the ground ranges could be predicted at specific altitudes. It is important to note that, even though the aircraft was beyond the reported data range for no connection (and confidence differences), there was not a distinct loss of connection. The aircraft could still intermittently detect the ground station as far as 24 nm ground range at 20,000 feet AGL. However, connectivity outside the ranges determined during flight testing would be too inconsistent to utilize operationally. Therefore, the aircraft could continue to transmit and receive data from the ground station beyond the boundaries reported in the flight test data, but link reliability would be extremely poor. Operational users utilizing an 802.11b wireless network for this purpose would need to understand that there is not a defined discrete boundary for the No Connection area like there is for the High to Low Data Rate boundary.

The test team also considered possible interference effects when reducing the flight test data. Since the Network Stumbler software recorded all 802.11b wireless devices detected by the aircraft, possible interference sources were also recorded. The location and transmitting power of these other wireless devices could not be determined, but the SNR and the detection time/duration of the devices detected by the aircraft were recorded.

The 802.11b wireless protocol provides 14 discrete channels between 2.4 and 2.5 GHz. Channels 1 through 11 are available in the United States. All data points for this objective were executed on Channel 11, transmitting at a center frequency of 2.426 GHz. During the 20,000 feet AGL data points, the ground station was the only 802.11b wireless device detected by the aircraft. During the 15,000 feet AGL data points, one 802.11b wireless device was detected on channel 11 during run 9, detailed in table D-3 of appendix D. The 802.11b wireless device transmitting on channel 11 was detected for ten seconds with a constant SNR of 7 when the aircraft was 19.1 to 18.2 nm from the ground station. The no connection data range for run 9 was 16.2 nm, well below the average of 18.23 nm. The standard deviation for the 15,000 feet AGL runs was 1.03, resulting in a standard deviation difference of 2 for run 9. Since the possible interference source was detected by the aircraft 2.0 nm from the No Connection boundary recorded during run 9, it cannot be concluded that interference caused reduced data range. However, it was the only explanation based on the available flight test data. **Determine the impact of additional 802.11b wireless devices sources transmitting on the same channel as the ground station. (R1)[1]**

The effect of aspect angle on ground range for negotiated data rate was determined using Flight Profile Two of appendix C. The antenna specifications provided by the manufacturer showed a purely isotropic antenna pattern. However, the aircraft could produce multipath or masking effects of the antenna, so testing was required to determine if the antenna remained isotropic when installed on the aircraft. The antenna was assumed to be symmetric about the long axis, so the antenna was investigated for 180 deg at 11.5 deg increments. Figure 3 shows the polar range plot for negotiated data rate based on ground range from the aircraft to the ground station at

[1] Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

10,000 feet AGL. Several additional 802.11b wireless devices transmitting on channel 11 were observed during the aspect angle data runs of Flight Profile 2 (more than any other sortie flown during the test program). During the 11.5, 55.5 and 79.5 deg runs, additional 802.11b wireless devices transmitting on channel 11 were detected by the aircraft. The circled regions of the plot illustrate the runs where additional 802.11b wireless devices were detected.

Table D-7 of appendix D summarizes the ground data ranges from low data rate to no connection recorded during the aspect angle flight test. The ranges for the three runs with possible interference sources all fell within one standard deviation (±1.55) of the mean (15.83 nm), so there did not appear to be any direct correlation between the data rate boundary and the additional 802.11b wireless devices. No additional 802.11b wireless devices were detected during the 90, 113, and 158 deg aspect angle runs. However, all three runs resulted in a data range for the low data rate greater than one standard deviation from the mean. Since interference could be ruled out as a causal factor for the decrease in reception range, the antenna was found not to be isotropic when installed on the aircraft. **Determine the antenna reception pattern when installed on the aircraft. (R2)**

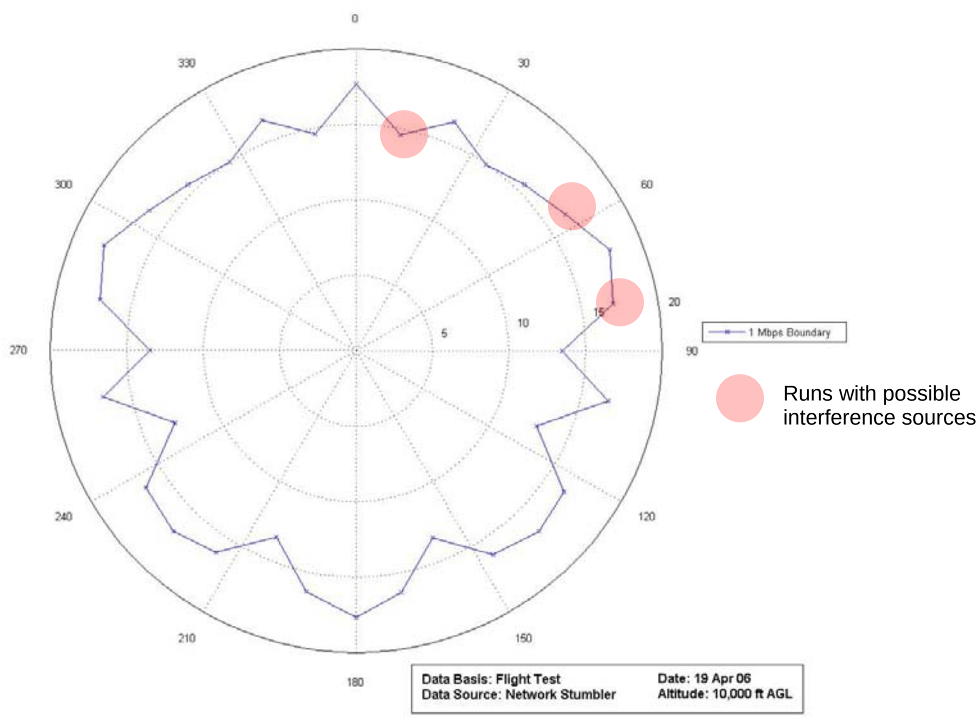

Figure 3: Low Data Rate Reception Boundary with 95 Percent Confidence

Datalink Performance Characteristics

Network throughput and packet health characteristics were measured within the two ranges previously discussed—Low Data Rate connection area and High Data Rate connection area. Throughput was measured by calculating the number of bytes of data sent from the ground station to the aircraft over a sixty second test point, during which the aircraft was either flown straight and level or banked at an angle of 20 or 30 deg. Any packets lost during transmission or resent over the link were recorded and used to determine the Transmission Control Protocol/Internet Protocol (TCP/IP) network's ability to handle errors in the data stream.

Procedures

The test points from Flight Profile 3 of appendix C were flown to determine datalink performance characteristics for the 0, 20, and 30 deg test points within the High and Low Data Rate connection areas. The flight profile was executed at 20,000 and 5,000 feet AGL using two different 802.11b wireless channels. Each test point was flown exclusively in either the High or Low Data Rate connection areas. During each test point, the test team transmitted either still imagery or video over the 802.11b wireless datalink in one minute time intervals. For still imagery test points, the datalink was saturated by initiating a data transfer large enough to require full link capacity during the entire test point. The evaluation of imagery with the electronic display unit was performed simultaneously with the collection of network performance data. The utility of the electronic display unit is discussed in a separate section.

Datalink Performance Results

The following table summarizes the 802.11b wireless datalink throughput recorded during flight testing. The tabulated values represent the amount of data, expressed in millions of bytes, transferred during each one minute test point at the specified altitude, connection area, bank angle and channel.

Table 3: Datalink Utilization Results for One Minute Test Points

	CHANNEL 6				CHANNEL 11			
Bank Angle	**5K ft AGL High Rate (10^6 Bytes)**	**20K ft AGL High Rate (10^6 Bytes)**	**5K ft AGL Low Rate (10^6 Bytes)**	**20K ft AGL Low Rate (10^6 Bytes)**	**5K ft AGL High Rate (10^6 Bytes)**	**20K ft AGL High Rate (10^6 Bytes)**	**5K ft AGL Low Rate (10^6 Bytes)**	**20K ft AGL Low Rate (10^6 Bytes)**
0 deg	34.31	26.83	6.74	30.21	33.99	18.00	25.44	18.03
20 deg	15.18	19.14	6.26	23.78	32.38	25.26	23.17	9.67
30 deg	7.29	29.24	2.73	20.94	36.33	7.15	5.13	7.40

Throughput was initially compared for 0 deg of bank at each altitude and connection area. This is illustrated in figure D-9 and D-10 of appendix D. Note that the throughput was highest overall and most consistent at 5,000 feet AGL in the High Data Rate connection area. The SNR was also highest in this connection area, and the slant range was less than in the 20,000 feet AGL altitude test points.

The results from the previous section showed that overall reception range increased with altitude. However, the results from this section demonstrated that throughput actually decreased with increasing altitude in the same data rate region. The results from the previous section also showed that only the 5,000 feet AGL altitude produced a consistent 11 Mbps negotiated data rate within the High Data Rate connection area. Therefore, although the boundaries for the High Data Rate connection area were consistent at 5,000 and 20,000 feet AGL, the maximum performance was only available when the slant range was within 2.0 nm. Throughput at 20,000 feet AGL was similar in both the High and Low Data Rate connection areas.

Throughput for the Low Data Rate test point slightly outperformed the High Data Rate test point at 20,000 feet AGL. The opposite result was expected; the network should have transferred more data at a higher SNR. The cause of this result can be seen in figure D-13 of appendix D. Areas of reduced data rate were observed where the slope of the line for the High Data Rate test point became shallow or flattened out completely. The reason this occurred was unknown, but it indicated there were periods of dropouts or reduced network performance. More testing would be required to see if this result was an anomaly, or if it can be attributed to another factor. The same data are also depicted in figure D-9 of appendix D along with test points in the High Data Rate connection area flown at 20 and 30 deg angles of bank. Here, the zero bank angle test point was outperformed by the 30 deg bank angle test point. The effect of reduced network performance during periods of the zero bank angle test point was clearly visible.

Since Datalink Reception Envelope testing demonstrated that the antenna pattern was not isotropic, lower antenna gain regions degraded datalink performance as the ground distance between the aircraft and ground station decreased. Throughput was the lowest at 5,000 feet AGL in the Low Data Rate connection area. Throughput rate for this test point reduced substantially and nearly stagnated at seven seconds, then improved slightly at 27 seconds. Signal dropout was apparent at approximately 43 seconds, and the nodes re-connected and began transferring data at the very end of the test run. The elevation angle between the aircraft and the ground station at 5,000 feet AGL in the Low Data Rate had a significant impact on datalink performance due to destructive interference from multipath effects created by the surrounding terrain.

In general, maneuvering flight lowered network throughput, although it did so unpredictably. Figure D-11 and D-12 of appendix D illustrate the effect of bank angle over the duration of the one-minute test points. In a few cases, throughput actually increased with bank angle changes. This occurred most notably at 20,000 feet AGL with Channel 6 for the 30 deg bank in the High Data Rate connection area. Additionally, in-flight observation by the test team during Datalink Reception Envelope testing showed SNR fluctuations as the aircraft antenna banked away from and toward the ground station during the setups between runs. **Perform additional testing at discrete bank angles. (R3)**

Packet health characteristics were recorded during each test point. The parameters used for this investigation were output queue length, packets lost, and packets retried. Output queue length was an indicator of data transfer delays over the network. Analysis of the data showed that output queue length was negligible during all test points. Packets lost and retried were zero for all data runs. This indicated that the TCP used to transmit packets over the datalink provided sufficient error correction and was capable of handling all signal degradation and noise without requiring any packets to be resent.

In addition to still imagery and data files, streaming video files were also sent over the wireless network. The throughput of the streaming video files was erratic, being adversely impacted by operating system scheduling algorithms. The tablet PC did not have dedicated hardware to process the video and instead relied on the central processing unit (CPU) and system memory. The Windows® XP operating system did not provide a method to optimize the CPU, memory allocation and scheduling algorithm for the video application, so the full hardware capability could not be used. Rather, the video application shared CPU resources with resident background processes.

As the video transfer was initiated, the video player software began to cache data. After approximately 5 seconds of file caching, the data transfer halted while the electronic display unit attempted to open and play the video stream. The software was unable to negotiate a steady throughput from the PC at the ground station and the aircraft due to processing load. It is also important to note that dropouts occurred in both the low and high data rate connection areas. The Windows® XP Professional operating system was not designed to display streaming video over connections with data dropouts since the 802.11b wireless protocol was designed to work in homes and small office buildings having very stable connections.

A dedicated software solution would also improve streaming video performance. Software would consist of a basic operating system build with only the packages required to perform the task, namely a graphical user interface, video and audio drivers, human interface device (mouse/keyboard) drivers, network protocols and drivers, and TCP/IP file transfer software. This would eliminate much of the processor load experienced during the test due to the multitude of background applications running in Windows® XP Professional.

A display system with dedicated video processing hardware and optimized network capability should also be used for playing streamed video in the cockpit. This would remove much of the processor load and would result in an improvement in video startup times and playback quality. **Develop a dedicated operating system and software solution optimized for imagery and streaming videos. (R4)**

Electronic Display Unit Utility

This test objective was to evaluate the utility of having an electronic display in the cockpit for viewing still imagery and motion video.

Procedures

The electronic display unit, an Itronix® Duo-Touch Tablet PC, was used to display images and video transferred over the 802.11b wireless network. The C-12C was flown in both the high and low data rate areas, in various bank angles (0 deg, 20 deg, 30 deg), at 5,000 feet and 20,000 feet AGL, and on two channels (6 and 11) for a minimum of one minute according to table D-5 of appendix D. The one minute minimum was imposed to ensure enough data were collected to properly analyze the network characteristics during each maneuver. The test conductor (TC) randomly chose the order of the test points and the pilot not flying (PNF) had 30 seconds to analyze the selected file. Qualitative pilot comments were recorded by the test conductor during the video transfers. Following the 30-second imagery evaluation, the TC would ask the PNF the questions specified below.

All still imagery was in 1024x768 pixel Joint Photographic Experts Group format, with file sizes from 134 to 300 KiB (1 KiB=2^{10} bytes). The video files were in three formats—Windows® Media Video (WMV), Moving Picture Experts Group (MPEG), and Audio-Video Interleaved (AVI), in file sizes from 9.5 MiB (1 MiB=2^{20} bytes) to 3.2 GiB (1 GiB=2^{30} bytes). The imagery was viewed using the Windows® Picture and Fax Viewer and the video was played using Windows® XP Media Player Classic. The video was played in streaming mode with the electronic display by selecting the video file stored at the ground station PC. Table D-6 of appendix D lists the size, type, and format of the imagery and video files.

Still Imagery Results

Still imagery results will be discussed first. A total of 21 still imagery test points were conducted—twelve at 20,000 feet AGL and nine at 5,000 feet AGL. The TC surveyed the PNF on the following items after the 30 second time limit:

- Visibility of electronic display in direct sunlight
- Visibility of electronic display in indirect sunlight
- Resolution sufficient to detect objects
- Resolution sufficient to distinguish between objects
- Resolution sufficient to identify objects
- Usefulness of electronic display

The questions were answered according to the Air Force Flight Test Center 6-point general-purpose scale.

6 – Very Satisfactory
5 – Satisfactory
4 – Marginally Satisfactory
3 – Marginally Unsatisfactory
2 – Unsatisfactory
1 – Very Unsatisfactory
N/A – Not applicable

In general, the pilots found the electronic display very useful. The ability to get real time target imagery in the cockpit was invaluable to the war fighter. The imagery used during testing had a white triangle over the intended target, along with coordinates in the lower left corner for the target location. The target coordinates were legible if the background color was dark, but became difficult to read if the background was lighter. The ability to mark the imagery prior to transmission from the ground station significantly enhanced the pilot's ability to identify the intended target with minimal communications.

Of particular note was the sun angle with respect to the display unit. In direct sunlight, the Itronix® screen became almost unusable. To avoid sunlight, the test pilots used body parts, such as elbows and hands, to block the sun, or they physically moved the display unit. **Make the display unit readable in direct sunlight. (R5)**

Also important were the size and weight of the display unit and the temperature increase of the display unit as it was used. The Itronix® Tablet PC measured 10.5 x 7.25 x 2.5 inches and weighed approximately 6.9 lbs. The size and weight of the display unit posed significant concerns for ejection seat aircraft. There would be a significant possibility of severe injury during the ejection sequence. Also, the display unit would need a way of being secured for dynamic maneuvering. The heat from the display unit was also a concern. If the pilot were required to keep the display unit on his leg with power on for a long duration, the heat would become uncomfortable and create a safety of flight condition. **Make the display unit smaller, lighter weight, and cooler. (R6)**

A positive aspect to the electronic display unit was the ability to upgrade the hardware easily when new display technology or network optimization algorithms become available. Since the display unit operated independently of the aircraft subsystems, there was more flexibility in software choices.

Figure 4 shows the data from the pilot surveys for the imagery files. Note that "Visibility in direct sunlight" has 8 counts in the unsatisfactory column. In contrast, the "Visibility in indirect sunlight" has 13 counts in the satisfactory column.

Another interesting outcome was that the "Resolution to identify objects" counts appear to be scattered almost randomly. This result was a combination of the electronic display, imagery resolution and specific imagery content. In general, when the target was a large object such as a building, the pilots were able to correctly identify the target of interest. However, if the target was a smaller object such as a car or truck, it was difficult for the pilots to determine exactly what the target was. Finally, the majority of the “Resolution to detect targets” counts were in the satisfactory column (10 of 21), but the majority of the “Resolution to distinguish objects” counts were in the marginally satisfactory column (9 of 21).

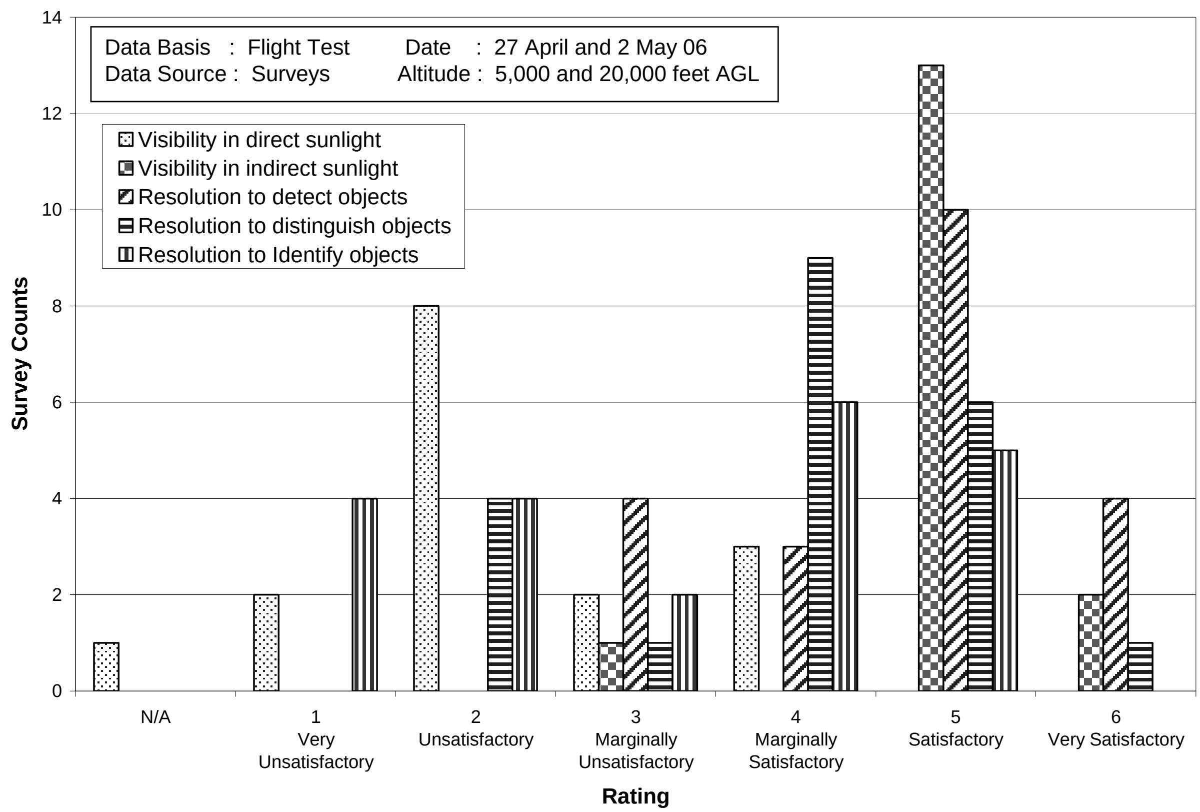

Figure 4: Imagery Survey Results

Streaming Video Results

Next, video results will be discussed. A total of 15 video test points were conducted—seven at 20,000 feet AGL and eight at 5,000 feet AGL. The following survey items were addressed concerning the video files:

- Visibility of electronic display in direct sunlight
- Visibility of electronic display in indirect sunlight
- Video plays without dropouts, skips, or frame freezes
- Pixilation minimized to detect objects
- Pixilation minimized to distinguish between objects
- Pixilation minimized to identify objects
- Usefulness of electronic display

The same rating scale was used for the video as for the still imagery. The video files presented significant problems during testing. Generally, the video files would not play in the low data rate area. Also, the larger files (greater than 50 MiB) occasionally would not open before the one minute of data collection time expired, so no data were collected for the video survey. When the files would open and begin playing, the MPEG video file usually ran at much lower frame rates than the WMV video file. During post processing it appeared as if the WMV video files were actually buffering before playing, not actually streaming. The MPEG videos would stream, which resulted in lower frame rates. The AVI file had similar play characteristics to the MPEG video files.

Regardless of file type, the video played better in the high data rate area versus the low data rate area, as expected. Video of a run-in to the target along the attack axis at altitude would be even more valuable than the target imagery alone. A real-time video of current battlefield / target conditions could provide large increases in aircrew situation awareness. However, a frame rate of 15 frames per second or more would optimize the video quality. At the same time, even if the video did not play at greater than 15 frames per second, the individual frames were still very clear and usable. Another option would be copy the video file before playing. The file size would need to be appropriate for the datalink speed and desired transmission time. Some video quality, such as color depth, could be sacrificed to reduce file size. Also, items such as size and bit rate encoding could help further reduce file size. **Determine the best media format for streaming video. (R7)**

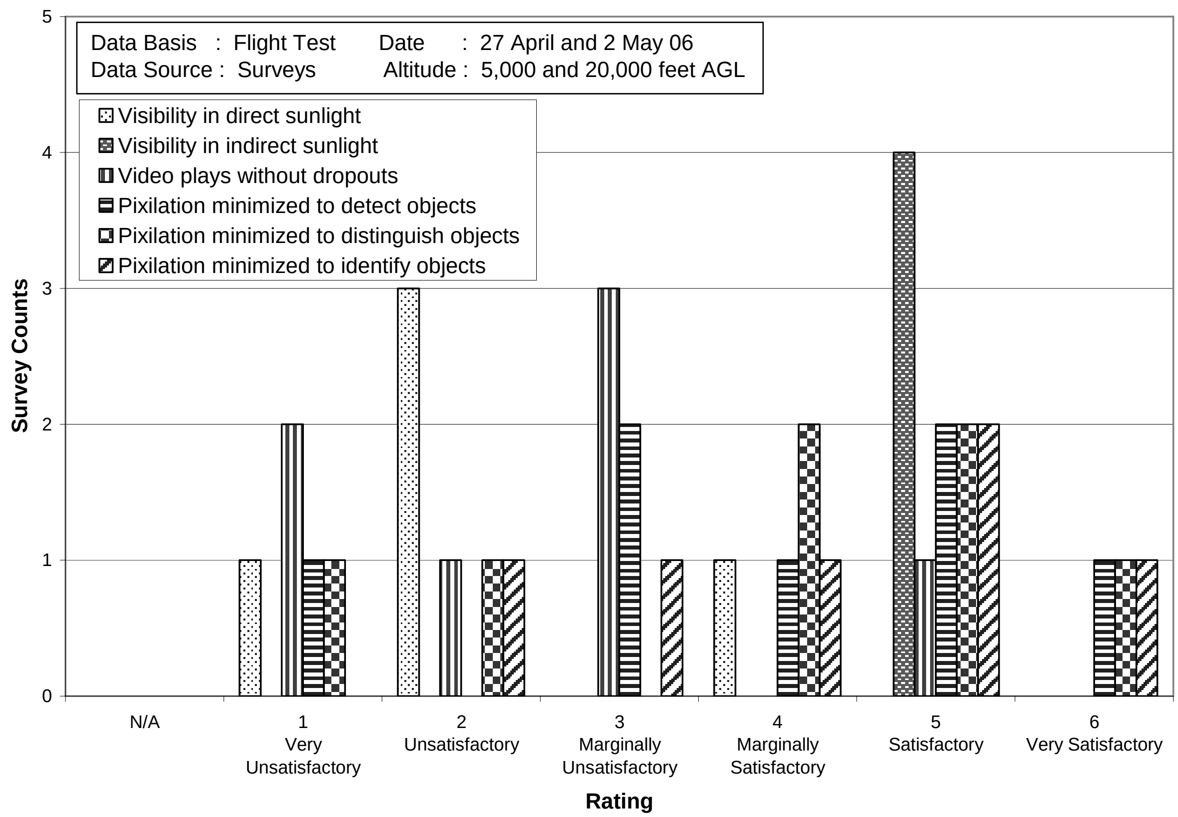

Figure 5: Video Survey Results, Low Data Rate

Figure 5 displays the results of the video survey in the low data rate area. Direct sunlight was still a problem for the video files. Four of the seven low data rate video transfers resulted in a rating of unsatisfactory or below. For the indirect sunlight case, four of the seven ratings were satisfactory. For video dropouts, six of the seven tests were in the unsatisfactory range. The other results vary depending on the type of video played.

Figure 6 displays the results of the video survey in the high data rate area. The video results in the high data rate clearly showed the increased performance over the low data rate area. The pixilation being minimized to detect, distinguish, and identify objects was clearly satisfactory. There were dropouts and skips as evidenced by the equal scattering of the "Video plays without dropouts" counts. As stated before, this result was due to the video format. The MPEG and AVI video files still had more dropouts than the WMV video files. The lower rating "Video plays without dropouts" counts are attributed to the AVI and MPEG video files.

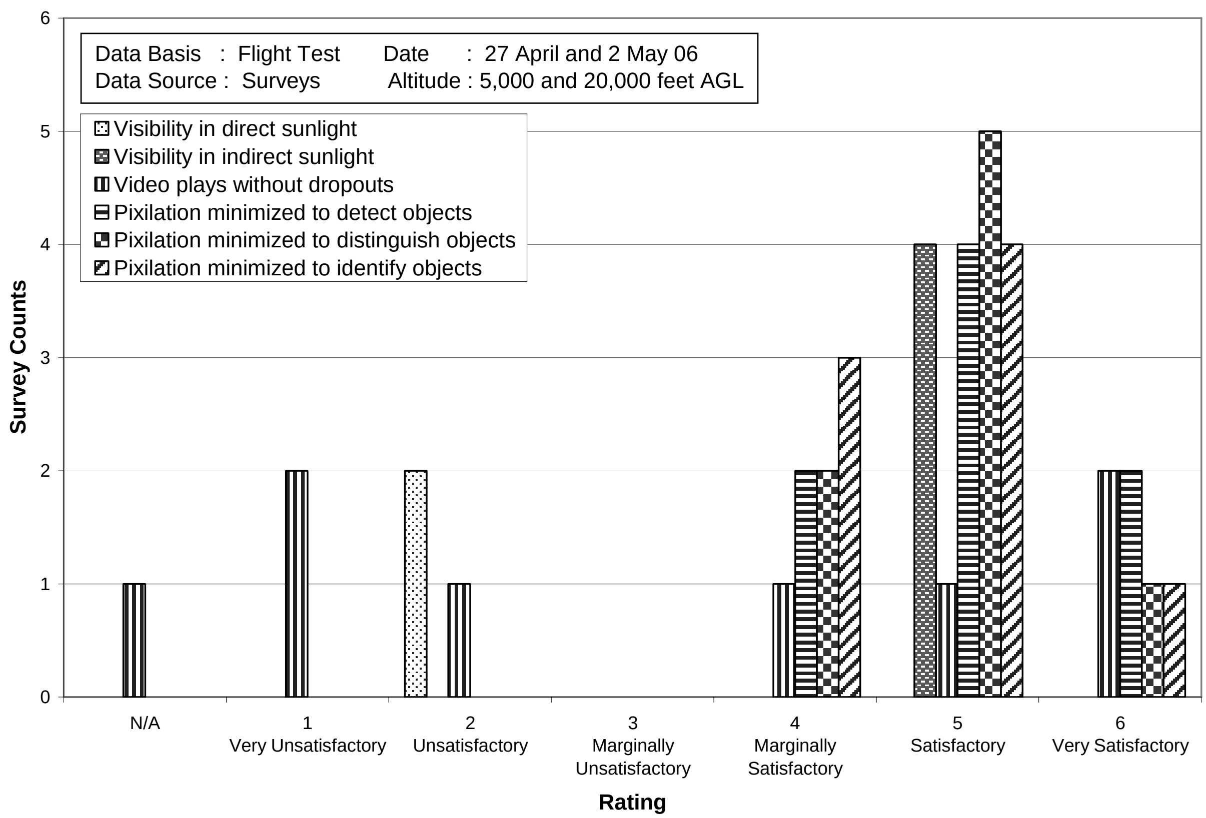

Figure 6: Video Survey Results, High Data Rate

Finally, an overall usefulness plot is shown in Figure 7. The results show the pilot satisfaction with the electronic display when viewing imagery. Video in the High Data Rate area depended upon the video encoding. Video in the Low Data Rate was generally regarded as unsatisfactory.

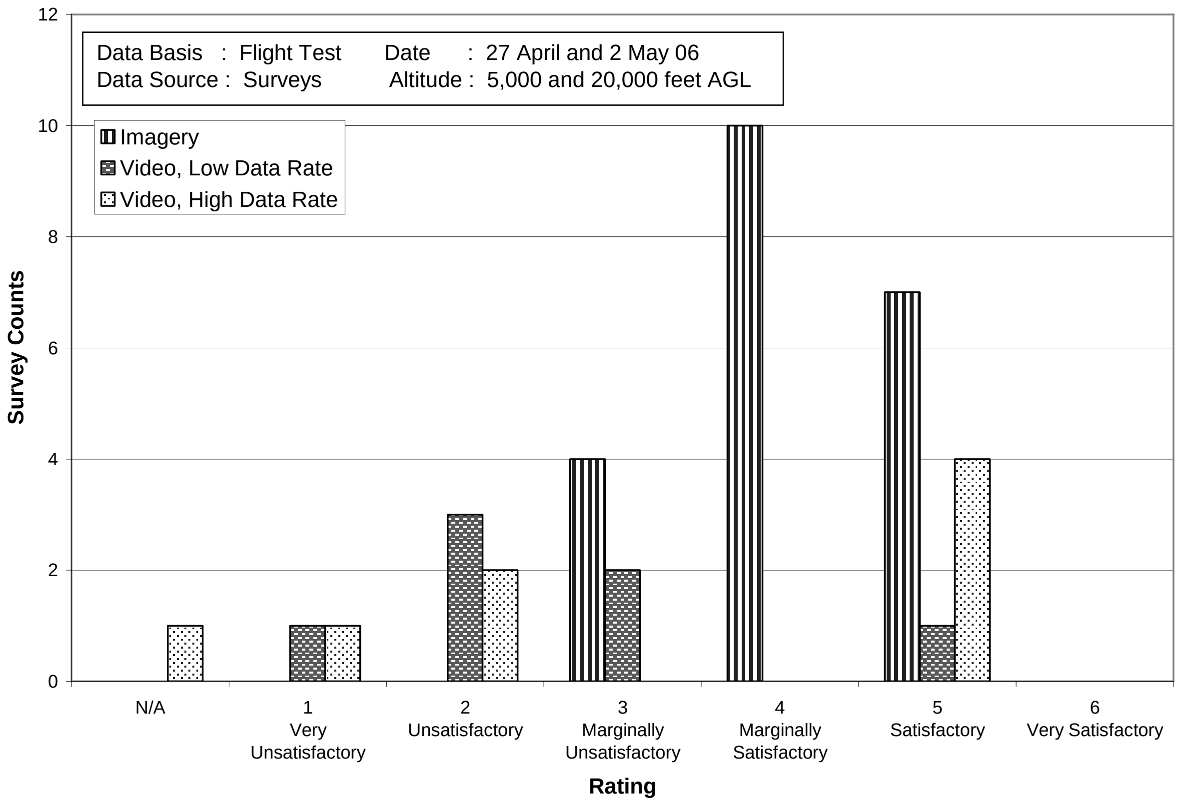

Figure 7: Overall Usefulness Survey Results

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CONCLUSIONS AND RECOMMENDATIONS

The HAVE HALO 802.11b wireless air-to-ground datalink performance was satisfactory in its tested configuration for transmitting high resolution imagery. However, it was not adequate in its tested configuration to provide reliable time-critical targeting streaming video. The datalink reception envelope provided operationally useful data ranges, with low data rate connections established between the aircraft and ground station at ground distances greater than 15 nm for 5,000, 10,000, 15,000 and 20,000 feet AGL.

Hardware and software constraints prevented full datalink utilization. To maximize datalink throughput and utility, a specialized operating system dedicated to 802.11b wireless datalink transmissions could be developed. Such a system would be designed to cope with potential dropouts, and it would be optimized for imagery and streaming video display. The testing performed by the HAVE HALO test demonstrated the potential utility of using the 802.11b wireless protocol to transmit high resolution imagery and streaming video from a ground station to an aircraft. The test also determined the operational benefits of high resolution target imagery and streaming video sent from a ground station to an aircraft to increase the pilot's situational awareness, but determined that the electronic display unit used during testing would not be suitable for that role.

The system under test (SUT) provided operationally useful ground data ranges at 5,000, 10,000, 15,000, and 20,000 feet AGL for the 802.11b wireless datalink. The 802.11b wireless datalink supported average High Data Rate connections up to 6.75 – 7.21 nm and average Low Data Rate connections from 14.90 – 18.43 nm, depending on altitude. However, the SUT as configured for this test could not support consistent streaming video data transfers across the datalink and would be unsatisfactory for operational pilots. The operational benefit of high resolution imagery and streaming video was validated, but the electronic display unit evaluated during testing would be unsuitable for that role. However, the 802.11b wireless datalink has the potential to provide time-critical high resolution and streaming video to pilots from a ground station to increase the pilot's situational awareness. The following conclusions and recommendations are prioritized in terms of safety of flight and impact to follow-on testing**.**

Flight testing at 15,000 feet AGL during Datalink Reception Envelope testing identified reduced ground range when additional 802.11b wireless devices were transmitting on Channel 11. Therefore, the possibility of interference exists when 802.11b wireless devices transmit on the same channel.

Determine the impact of additional 802.11b wireless devices sources transmitting on the same channel as the ground station. (R1, page 7)

The current SUT does not provide dedicated video processing capability and is not optimized for data connections with dropouts. A configuration incorporating these capabilities would allow the pilot to optimally use the datalink.

Develop a dedicated operating system and software solution optimized for imagery and streaming videos. (R4, page 11)

Streaming video performance will vary greatly based on available data rate and link stability. Determining the optimum media format would maximize datalink utility.

Determine the best media format for streaming video. (R7, page 15)

The current display unit is too large and heavy for pilots to effectively use for long periods of time. Also, the display unit becomes hot after continued use, making the pilot uncomfortable. A smaller, lighter and cooler electronic display unit the pilot could more easily manipulate would improve utility and reduce safety of flight issues during high dynamic maneuvering and ejection. Another solution would be to incorporate the electronic display unit functionality into a multi-function display (MFD). The pilot would then be free from ejection and dynamic maneuvering concerns. Also, he would not have responsibility of carrying the display unit to the aircraft or the possibility of damaging the unit. Finally, most fighter and newer transport aircraft already have MFDs incorporated into the cockpit.

Make the display unit smaller, lighter weight, and cooler. (R6, page 13)

The electronic display unit is almost unreadable in direct sunlight, which reduces its utility.

Make the display unit readable in direct sunlight. (R5, page 13)

Testing the aircraft in an anechoic chamber would provide the most accurate antenna profile pattern without additional environmental variables present during flight testing.

Determine the antenna reception pattern when installed on the aircraft. (R2, page 8)

Testing 802.11b wireless datalink performance during continued flight at discrete bank angles will fully demonstrate the effects of bank angle away from and toward the ground station.

Perform additional testing at discrete bank angles. (R3, page 10)

REFERENCES

1. Milner, Marius. *NetStumbler v. 0.4.0,* mariusm@pacbell.net, http://www.stumbler.net, 21 April 2004.

2. Technical Order 1-C12A-1 Operator's Manual, USAF Series, November 2003.

3. Taschner, Michael J. *Modification Flight Manual: C-12C, Serial Number 73-1215*, Department of Defense, Edwards AFB CA, 23 September 2002.

4. Gawell, Lynnette J.F. *Modification Operational Supplement: C-12C, Serial Number 73-1215*, Department of Defense, Edwards AFB CA, March 2005.

5. Tran, Luan. *GAINR-Lite System Installation Package*, JT3, LLC, Edwards AFB, CA, Feb 2005.

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APPENDIX A – DETAILED TEST ARTICLE DESCRIPTION

The system under test (SUT) consisted of airborne and ground station antennas with amplifiers, IBM® ThinkPad PCs with Windows® XP Professional, datalink performance collection software for the ground and aerial nodes, the Itronix® DuoTouch tablet PC for the electronic display unit, two Cisco® Aironet 1200 wireless access points, and two GARMIN® GPS units for datalink synchronization. The airborne and ground datalink transmitters operated at 4 Watts over the omnidirectional antennas at a frequency of 2.4 GHz to 2.5 GHz. The SUT airborne GPS receiver was spliced into a GPS antenna mounted on the tail of the C-12C. Table A-1 lists the components that used during testing.

The Itronix® electronic display unit and the IBM® ThinkPad PCs at the aircraft and ground stations used specific performance statistic software packages to collect data. To characterize the data reception envelope, the Network Stumbler package recorded signal-to-noise ratio and negotiated data rate between the aircraft and the ground station. To collect the throughput, utilization, and packet statistics data, Microsoft® Performance Monitor was configured to record datalink parameters at the ground station.

Table A-1: Components of the SUT for the HAVE HALO TMP

Component	**Model**	**Manufacturer**
Aerial Blade Antenna	6030-2	Haigh-Farr
Ground Antenna	6030-2	Haigh-Farr
10-20 dB Attenuator	768-20	Narda
5 Watt Amplifier	HA2405GTI-NF	Hyperlink Technologies
GPS Receiver	GPSMAP 296	GARMIN®
Duo Touch Tablet PC	IX325	Itronix®
IBM® ThinkPad	T-40	IBM®
Wireless Access Point	AIR-AP1220B	Cisco®
5-Port Switch	EZXS55W	Linksys®
Network Card	ORiNOCO 8470-FC	Proxim®

Figure A-1 shows the hardware installed on the C-12C, Tail # 73-1215 minus the wireless access point. Figure A-2 is a schematic of the hardware on the C-12C. Figure A-3 is a schematic of the hardware at the ground station. Finally, figure A-4 shows the location of the externally mounted Haigh-Farr antenna.

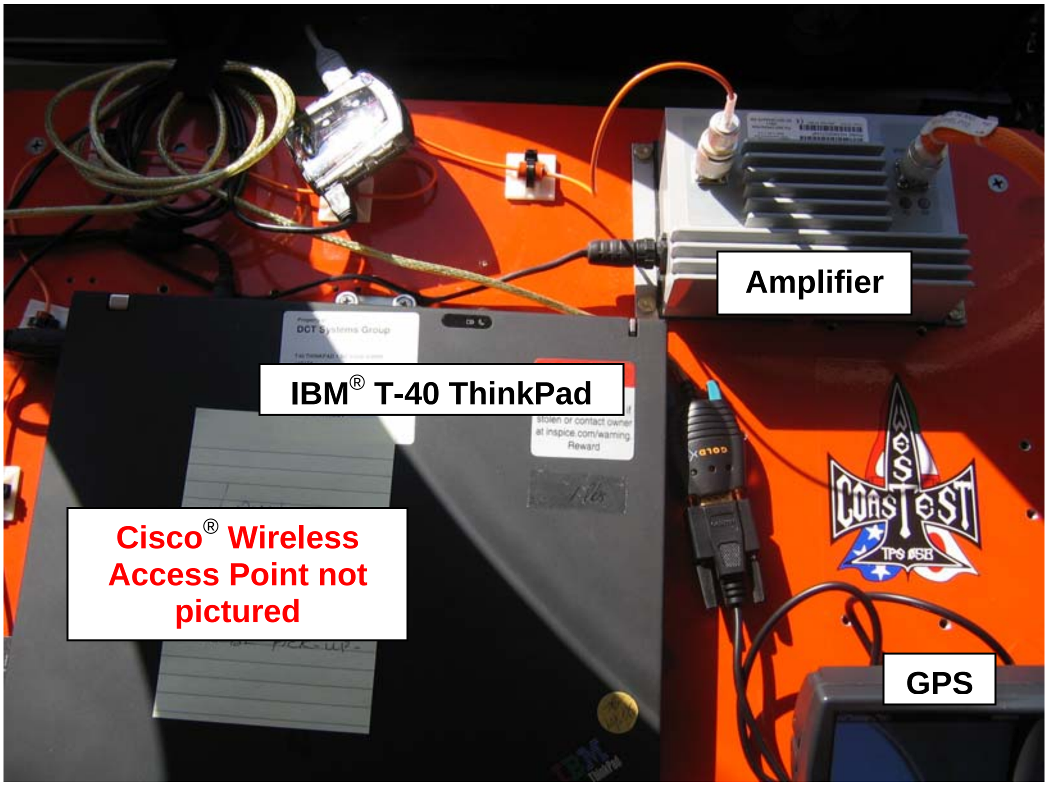

Figure A-1: C-12C Tail # 73-1215 Test Hardware

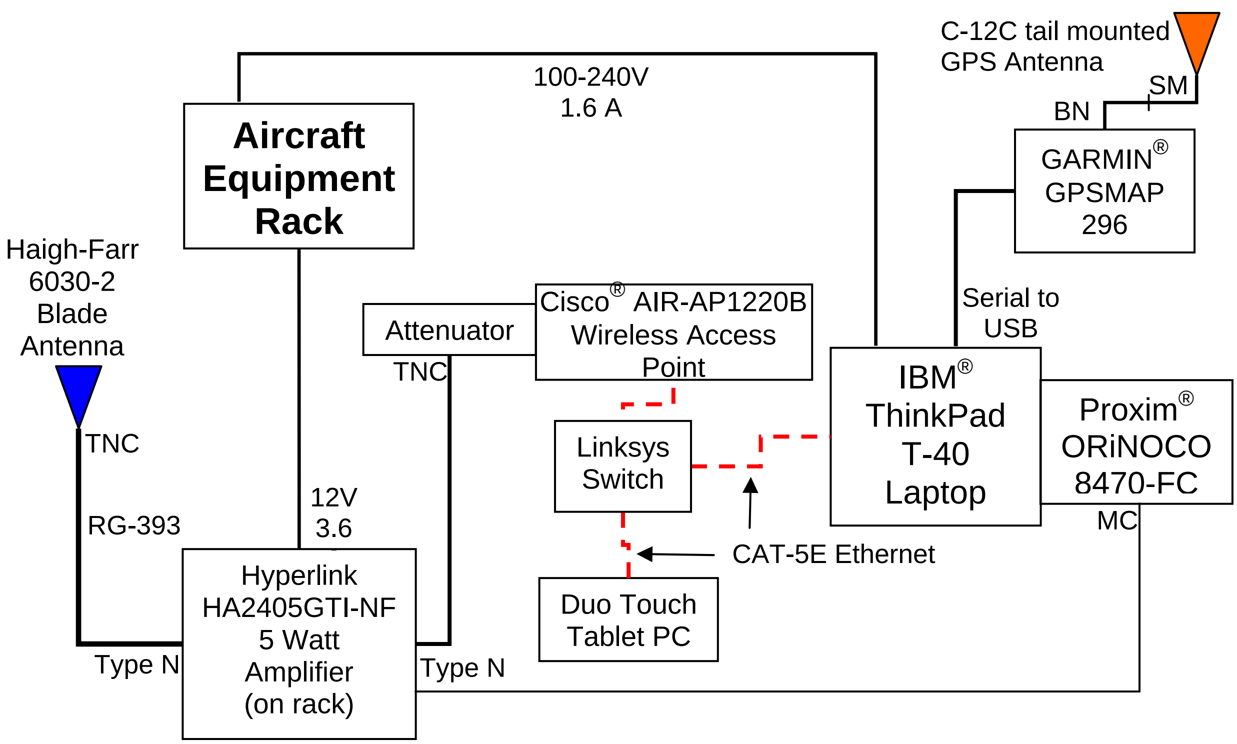

Figure A-2: C-12C Tail # 73-1215 Test Hardware Schematic

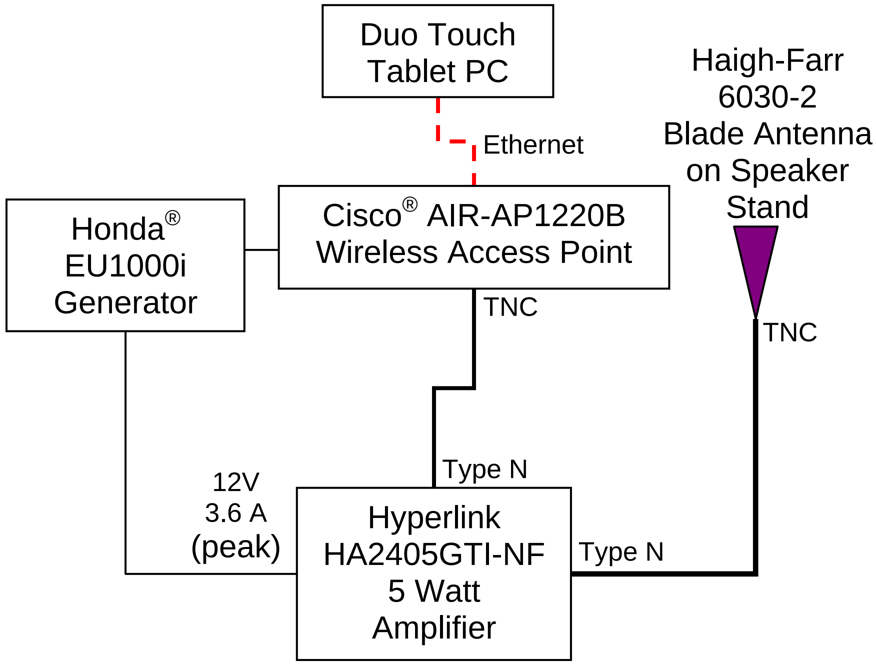

Figure A-3: Ground Station Hardware Scheme

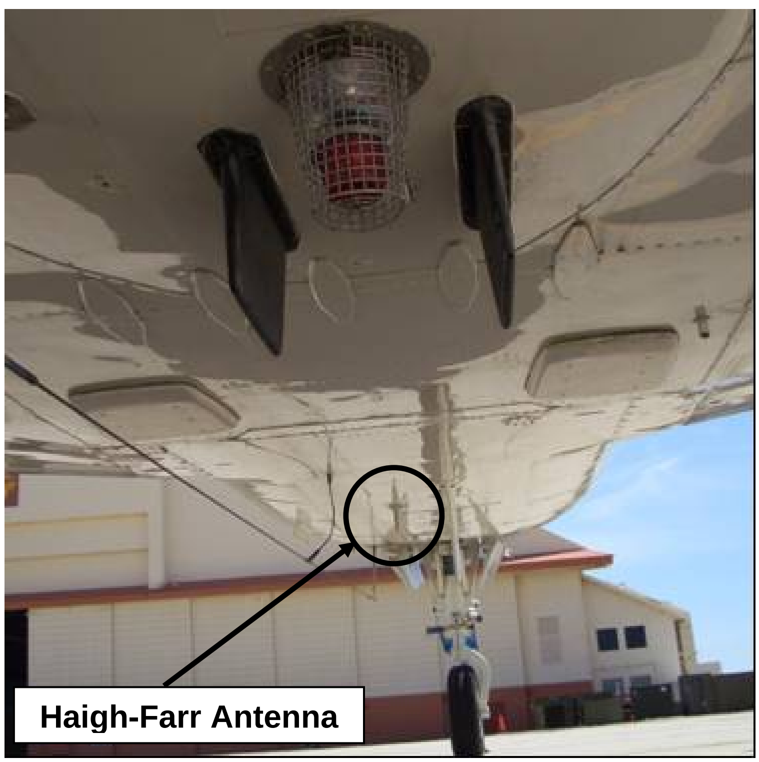

Figure A-4: C-12C Tail # 73-1215 Datalink Antenna

One C-12C Huron test aircraft, tail # 73-1215, was used to collect data for this test program. The C-12C was a Raytheon King Air twin-engine turboprop transport aircraft. A detailed description of the C-12C was found in the C-12C Flight Manual (Reference 2). Detailed descriptions of aircraft modifications were found in the Modification Flight Manual (Reference 3) and Modification Operational Supplement (Reference 4).

The test support hardware consisted of one truth source supplied by 412th Test Wing, Range Support Division Edwards AFB (412 TW/ENR). A GPS Aided Inertial Reference (GAINR) system was the truth source on C-12C #73-1215. According to Reference 5, the GAINR-II accuracy was identified at 1 foot accuracy. Figure A-5 illustrates the three components of the GAINR system.

Figure A-5: Components of the GPS Aided Inertial Reference System

APPENDIX B – MANEUVER SETS

Table B-1 summarizes the tasks completed on the seven sorties flown for the test program. Table B-2 summarizes the specific maneuver sets flown along with the flight conditions for the reception envelope testing and Table B-3 summarizes the same information for the data performance and in-flight electronic display testing.

Table B-1: HAVE HALO Test Summary

Date	Sortie #	Sortie Duration(hrs)	Tasks Completed
10 April 06	1	2	Flight Profile 1 5 runs at 5K ft AGL
12 April 06	1	2.8	Flight Profile 1 11 runs at 20K ft AGL
14 April 06	1	2.8	Flight Profile 1 11 runs at 10K ft AGL
18 April 06	1	2.5	Flight Profile 1 10 runs at 15K ft AGL 4 runs at 5K ft AGL
19 April 06	1	2.5	Flight Profile 2 16 runs at 10K ft AGL with 11.5° aspect separation
27 April 06	1	2.5	Flight Profile 3 7 runs at 5K ft AGL Ch A 12 runs at 5K ft AGL Ch B
2 May 06	1	2.5	Flight Profile 3 12 runs at 20K ft AGL Ch A 12 runs at 20K ft AGL Ch B 5 runs at 5K ft AGL Ch A

Table B-2: HAVE HALO Aircraft Maneuver Set For Reception Envelope Testing

Maneuver	Nominal Conditions	Remarks	Flight Profile
Straight and Level Unaccelerated Flight	180 KIAS, 5,000 ft AGL	DATA BAND: ±500 ft TOLERANCE: ±100 ft	1
Straight and Level Unaccelerated Flight	180 KIAS, 10,000 ft AGL	DATA BAND: ±500 ft TOLERANCE: ±100 ft	1 & 2
Straight and Level Unaccelerated Flight	180 KIAS, 15,000 ft AGL	DATA BAND: ±500 ft TOLERANCE: ±100 ft	1
Straight and Level Unaccelerated Flight	180 KIAS, 20,000 ft AGL	DATA BAND: ±500 ft TOLERANCE: ±100 ft	1

Table B-3: HAVE HALO Aircraft Maneuver Set For Datalink Performance and In-flight Electronic Display Testing

Maneuver	Nominal Conditions	Remarks	Flight Profile
Straight and Level Unaccelerated Flight	180 KIAS, 5,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft TOLERANCE: ±5 KIAS, ±100 ft	3
Straight and Level Unaccelerated Flight	180 KIAS, 10,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft TOLERANCE: ±5 KIAS, ±100 ft	3
Straight and Level Unaccelerated Flight	180 KIAS, 15,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft TOLERANCE: ±5 KIAS, ±100 ft	3
Straight and Level Unaccelerated Flight	180 KIAS, 20,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft TOLERANCE: ±5 KIAS, ±100 ft	3
Constant 20° Banked Turn	180 KIAS, 5,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 30° Banked Turn	180 KIAS, 5,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 20° Banked Turn	180 KIAS, 10,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 30° Banked Turn	180 KIAS, 10,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 20° Banked Turn	180 KIAS, 15,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 30° Banked Turn	180 KIAS, 15,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 20° Banked Turn	180 KIAS, 20,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3
Constant 30° Banked Turn	180 KIAS, 20,000 ft AGL	DATA BAND: ±5 KIAS, ±500 ft, ±2° Bank TOLERANCE: ±5 KIAS, ±100 ft, ±1° Bank	3

APPENDIX C – C-12C FLIGHT PROFILES

Flight Profile 1

Flight Profile 1 consisted of a single pass with the aircraft pointed directly at or away from the ground station. The aircraft began maneuvering at a range where no connection existed between the ground station and the aircraft. The aircraft flew directly at the ground station using a GPS aided track for repeatability. As the aircraft approached the ground station, the 802.11b network negotiated data rates in discrete intervals starting at 1 megabit per second (Mbps) up to a maximum of 11 Mbps. The aircraft continued until overflying the ground station and turned to set up for the outbound run. Flight Profile 1 defined the High Data Rate and Low Data Rate Zones for the air-to-ground datalink. The profile was flown at 5,000, 10,000, 15,000, and 20,000 feet AGL.

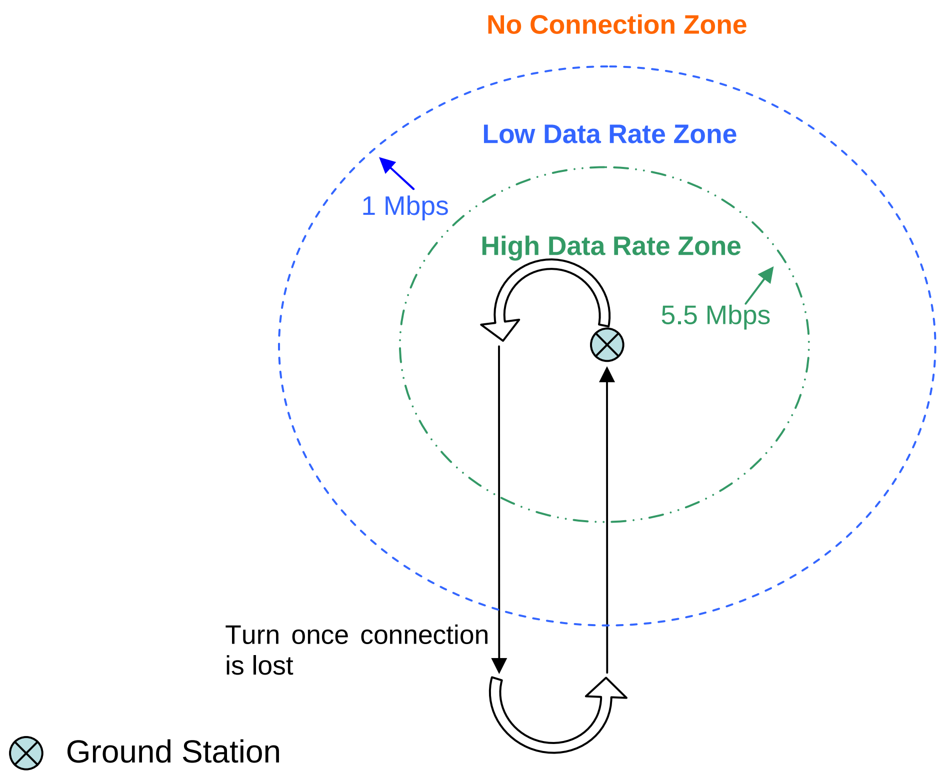

Figure C-1: Flight Profile 1

Flight Profile 2

Flight Profile 2 was used to determine the effect of antenna aspect angle. The aircraft began over the ground station and maintained straight and level unaccelerated flight until reaching the boundary between the low connection data range and no connection. The maneuver consisted of 16 discrete-angle runs with respect to the ground station at 10,000 feet AGL to cover 180 deg for the omnidirectional antennas. The ground station adjusted the ground antenna 23 deg after the outbound and inbound runs were complete. The ground track was GPS aided to ensure each aspect was accurately flown.

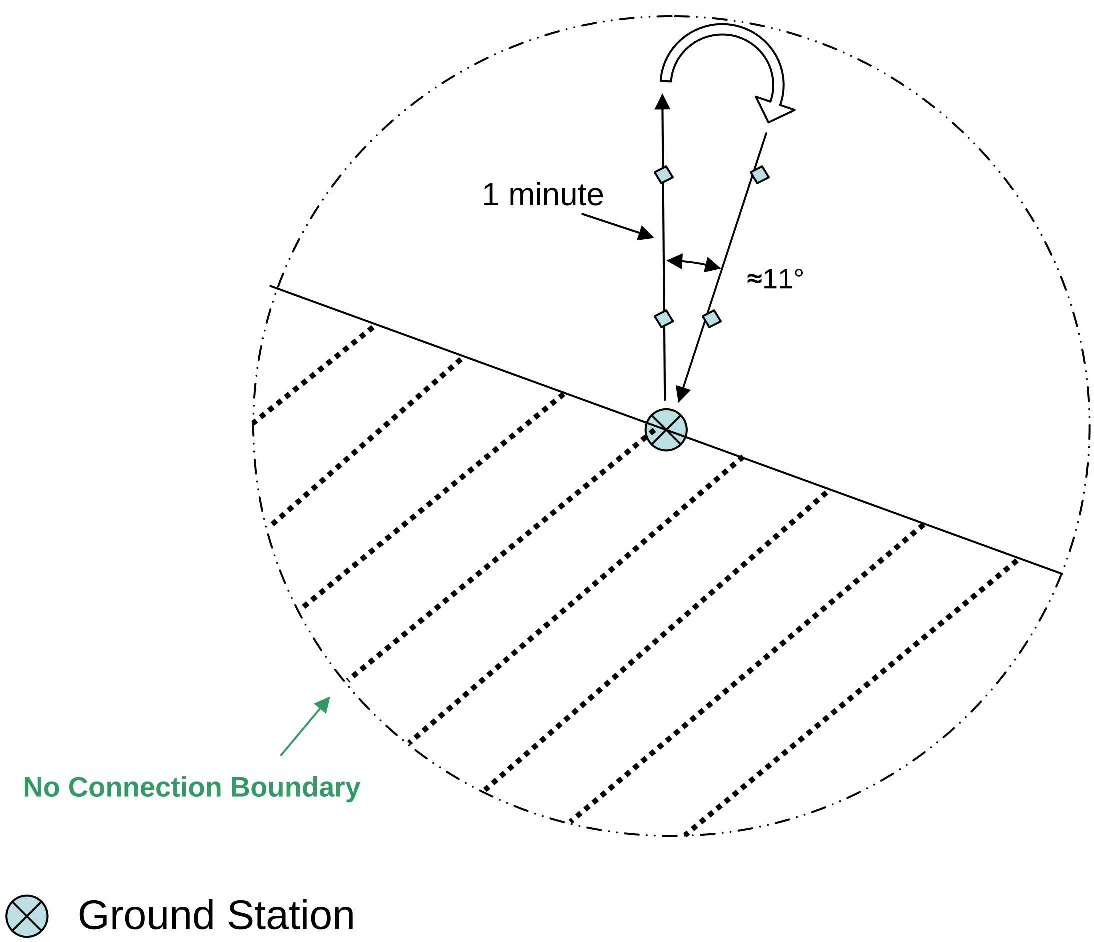

Figure C-2: Flight Profile 2

Flight Profile 3

Flight profile 3 was flown to gather datalink performance characteristics including: data rate utilization, packet health statistics, and pilot survey data based on image or video quality. The maneuvers were flown within either the Low Data Rate Zone or High Data Rate Zone. During each straight leg and throughout the turns, the test team transmitted still imagery or streaming video over the datalink in one-minute time intervals to satisfy the conditions for specific test points.

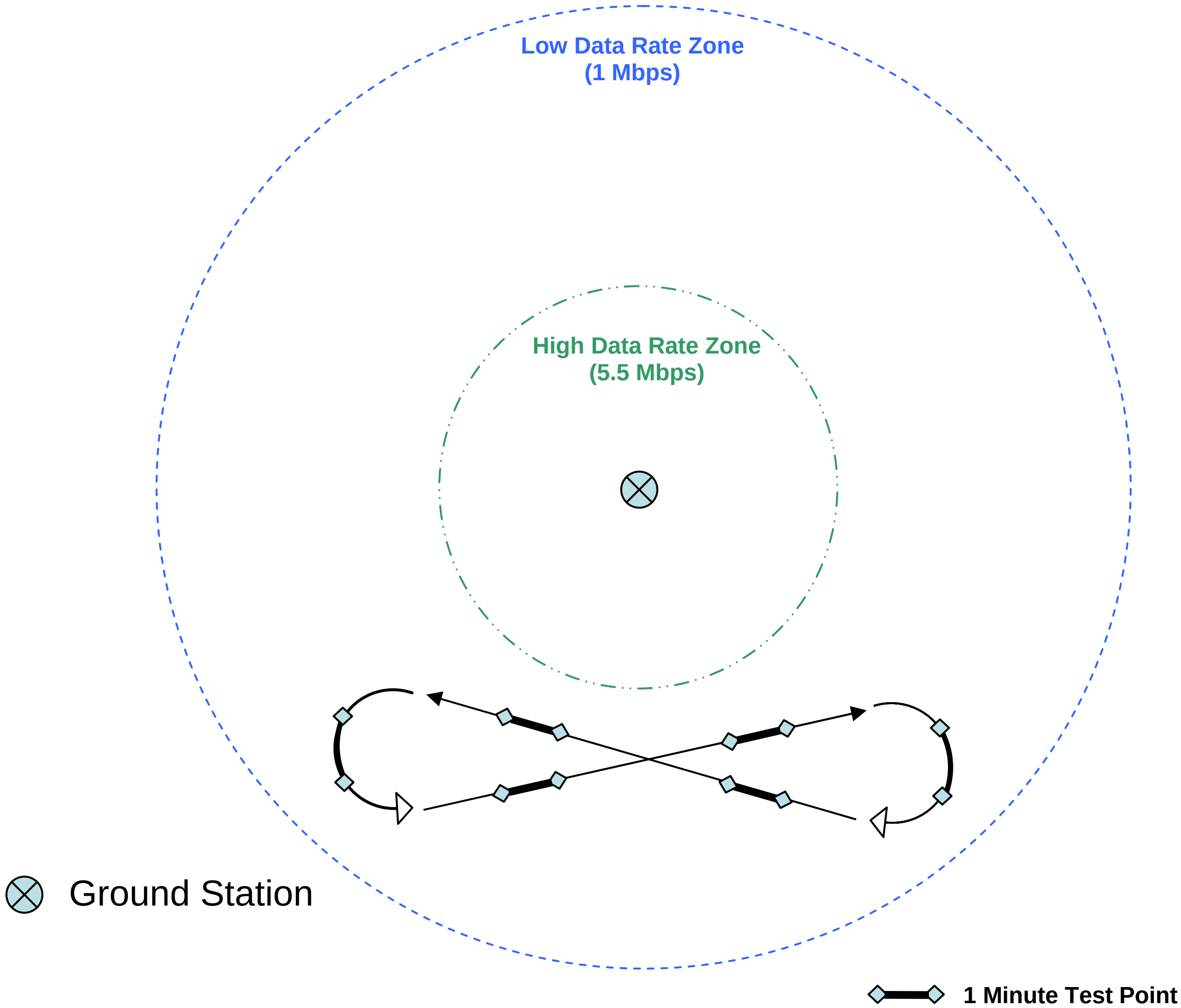

Figure C-3: Flight Profile 3

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APPENDIX D – FIGURES AND TABLES

Table D-1: Ground Range Distance Summary for Flight Profile 1 at 5,000 feet AGL

Run Number	Inbound/ Outbound	Altitude (MSL)	11Mbps (nm)	5.5Mbps (nm)	2Mbps (nm)	1Mbps (nm)	Start Run (Z)	End Run (Z)
1	Inbound	7800	2.2	7.5	11	16.5	17:02:00	17:08:24
2	Outbound	7800	2.2	6.5	10.9	16.5	17:09:45	17:15:28
3	Inbound	7800	2	7.5	11.2	16.1	17:17:10	17:24:00
4	Outbound	7800	2.4	7.5	8	15.5	17:24:30	17:28:24
5	Inbound	7800	2.4	7.6	10.9	15.8	17:30:24	17:34:27
1*	Outbound	7840	2.2	6.2	8.6	17.1	17:48:00	17:52:59
2*	Inbound	7840	2.4	5.9	7.9	16.2	17:55:12	18:00:20
3*	Outbound	7810	2.4	6	10.1	16.9	18:03:43	18:08:20
4*	Inbound	7900	2.2	6	11.4	19	18:10:59	18:16:37

*Test Points flown on different days

Table D-2: Ground Range Distance Summary for Flight Profile 1 at 10,000 feet AGL

Run Number	Inbound/ Outbound	Altitude (MSL)	11Mbps (nm)	5.5Mbps (nm)	2Mbps (nm)	1Mbps (nm)	Start Run (Z)	End Run (Z)
1	Inbound	12810	N/A	8.6	10.2	15.4	9:06:40	9:12:35
2	Outbound	12830	N/A	8.2	10.3	16.4	9:17:05	9:22:22
3	Inbound	12810	N/A	7.6	10.1	15.4	9:27:00	9:32:46
4	Outbound	12820	N/A	7.5	10.4	15.5	9:37:55	9:43:30
5	Inbound	12850	N/A	8.5	10.0	15.1	9:46:53	9:51:54
6	Outbound	12820	N/A	7.5	10.8	15.9	9:55:55	10:01:24
7	Inbound	12800	N/A	5.0	9.9	15.3	10:04:30	10:10:12
8	Outbound	12800	N/A	5.5	12.8	14.5	10:14:31	10:20:03
9	Inbound	12800	1.5	8.7	10.1	12.6	10:23:30	10:28:53
10	Outbound	12800	N/A	5.5	10.5	12.9	10:32:55	10:38:30
11	Inbound	12780	N/A	5.3	10.1	14.1	10:42:04	10:47:35

Table D-3: Ground Range Distance Summary for Flight Profile 1 at 15,000 feet AGL

Run Number	Inbound/ Outbound	Altitude (MSL)	11Mbps (nm)	5.5Mbps (nm)	2Mbps (nm)	1Mbps (nm)	Start Run (Z)	End Run (Z)
1	Outbound	17780	N/A	6.9	14.9	18.9	16:09:50	16:14:45
2	Inbound	17700	N/A	6.9	12.5	19	16:17:26	16:23:42
3	Outbound	17760	N/A	7.2	12.9	18.9	16:26:19	16:31:27
4	Inbound	17810	N/A	6.9	13.2	17.6	16:34:35	16:40:50
5	Outbound	17900	N/A	7.1	13.5	19.3	16:43:58	16:48:50
6	Inbound	17810	N/A	7.1	11.4	17.8	16:51:43	16:57:45
7	Outbound	17760	N/A	7.1	11.3	19.4	17:00:50	17:05:34
8	Inbound	17800	N/A	7.1	10.2	17.4	17:08:06	17:14:41
9*	Outbound	17780	N/A	7.2	11.4	16.2	17:17:12	17:20:59
10	Inbound	17900	N/A	7.1	12.2	17.8	17:25:33	17:32:31

*Significant interference encountered during test point

Table D-4: Ground Range Distance Summary for Flight Profile 1 at 20,000 feet AGL

Run Number	Inbound/ Outbound	Altitude (MSL)	11Mbps (nm)	5.5Mbps (nm)	2Mbps (nm)	1Mbps (nm)	Start Run (Z)	End Run (Z)
1	Inbound	22800	N/A	5	9.8	16.5	16:22:35	16:29:17
2	Outbound	22850	N/A	7.1	10.9	21.1	16:31:10	16:36:41
3	Inbound	22750	N/A	7	10.6	20.7	16:40:53	16:47:55
4	Outbound	22800	N/A	7.7	11.4	17.8	16:51:30	16:56:13
5	Inbound	22800	N/A	7.5	11.8	19.9	17:00:55	17:09:04
6	Outbound	22820	N/A	7.7	11.5	17.5	17:13:05	17:17:35
7	Inbound	22820	N/A	6.8	11.6	19.3	17:22:01	17:29:27
8	Outbound	22780	N/A	7.7	11	15	17:32:34	17:38:00
9	Inbound	22780	N/A	7.8	11.3	16.8	17:41:27	17:48:56
10	Outbound	22780	N/A	7.8	13	17.9	17:52:54	17:58:11
11	Inbound	22780	N/A	7.2	13.2	17	18:01:00	18:08:40

Table D-5: Test Points Flown for Datalink Analysis and Electronic Display Utility

Test Point	Data Type	Altitude (feet AGL)	Data Range	Bank Angle (Degrees)	802.11 Channel
1	STILL IMAGERY	20K	HIGH	0	6
2	PRERECORDED VIDEO	20K	HIGH	0	6
3	STILL IMAGERY	20K	HIGH	20	6
4	PRERECORDED VIDEO	20K	HIGH	20	6
5	STILL IMAGERY	20K	HIGH	30	6
6	STILL IMAGERY	20K	LOW	0	6
7	PRERECORDED VIDEO	20K	LOW	0	6
8	STILL IMAGERY	20K	LOW	20	6
9	STILL IMAGERY	20K	LOW	30	6
10	STILL IMAGERY	5K	HIGH	0	6
11	PRERECORDED VIDEO	5K	HIGH	0	6
12	STILL IMAGERY	5K	HIGH	20	6
13	PRERECORDED VIDEO	5K	HIGH	20	6
14	STILL IMAGERY	5K	LOW	0	6
15	PRERECORDED VIDEO	5K	LOW	0	6
16	STILL IMAGERY	5K	LOW	20	6
17	PRERECORDED VIDEO	5K	LOW	20	6
18	STILL IMAGERY	20K	HIGH	0	11
19	PRERECORDED VIDEO	20K	HIGH	0	11
20	STILL IMAGERY	20K	HIGH	20	11
21	PRERECORDED VIDEO	20K	HIGH	20	11
22	STILL IMAGERY	20K	HIGH	30	11
23	PRERECORDED VIDEO	20K	HIGH	30	11
24	STILL IMAGERY	20K	LOW	0	11
25	STILL IMAGERY	20K	LOW	20	11
26	STILL IMAGERY	20K	LOW	30	11
27	PRERECORDED VIDEO	20K	LOW	30	11
28	STILL IMAGERY	5K	HIGH	0	11
29	PRERECORDED VIDEO	5K	HIGH	0	11
30	STILL IMAGERY	5K	HIGH	20	11
31	STILL IMAGERY	5K	LOW	0	11

Table D-5: Test Points Flown for Datalink Analysis and Electronic Display Utility Continued

Test Point	Data Type	Altitude (feet AGL)	Data Range	Bank Angle (Degrees)	802.11 Channel
32	PRERECORDED VIDEO	5K	LOW	0	11
33	STILL IMAGERY	5K	LOW	20	11
34	PRERECORDED VIDEO	5K	LOW	20	11
35	STILL IMAGERY	5K	LOW	30	11
36	PRERECORDED VIDEO	5K	LOW	30	11

Table D-6: File Descriptions

Test Point	File Name	Data Type	Size	Pilot	Date	Order
1	135	JPEG	262 KB	Maj. Schwartz	2 May 06	19
2	O5B Systems Review	AVI	3.2 GB	Maj. Schwartz	2 May 06	20
3	136	JPEG	247 KB	Maj. Schwartz	2 May 06	21
4	To The Limit	WMV	100 MB	Maj. Schwartz	2 May 06	22
5	37	JPEG	299 KB	Maj. Schwartz	2 May 06	15
6	31	JPEG	264 KB	Maj. Schwartz	2 May 06	16
7	Liquid2	WMV	126 MB	Maj. Schwartz	2 May 06	18
8	32	JPEG	264 KB	Maj. Schwartz	2 May 06	14
9	33	JPEG	264 KB	Maj. Schwartz	2 May 06	17
10	24	JPEG	274 KB	Maj. Spinelli	27 Apr 06	1
11	Sniper	MPEG	446 MB	Maj. Spinelli	27 Apr 06	2
12	25	JPEG	274 KB	Maj. Spinelli	27 Apr 06	3
13	Liquid2	WMV	126 MB	Maj. Spinelli	2 May 06	33
14	27	JPEG	186 KB	Maj. Spinelli	2 May 06	34
15	Liquid2	WMV	126 MB	Maj. Spinelli	27 Apr 06	4
16	28	JPEG	186 KB	Maj. Spinelli	2 May 06	35
17	To The Limit	WMV	100 MB	Maj. Spinelli	2 May 06	36
18	1	JPEG	235 KB	Maj. Schwartz	2 May 06	26
19	WEB KWingWorls	WMV	9.5 MB	Maj. Schwartz	2 May 06	23
20	2	JPEG	187 KB	Maj. Schwartz	2 May 06	32
21	WEB KWingWorls	WMV	9.5 MB	Maj. Schwartz	2 May 06	31
22	3	JPEG	197 KB	Maj. Schwartz	2 May 06	28
23	O5B Systems Review	AVI	3.2 GB	Maj. Schwartz	2 May 06	27

Table D-6: File Descriptions Concluded

Test Point	File Name	Data Type	Size	Pilot	Date	Order
24	4	JPEG	257 KB	Maj. Schwartz	2 May 06	30
25	131	JPEG	268 KB	Maj. Schwartz	2 May 06	24
26	132	JPEG	295 KB	Maj. Schwartz	2 May 06	29
27	Liquid2	MWV	126 MB	Maj. Schwartz	2 May 06	25
28	7	JPEG	207 KB	Maj. Spinelli	27 Apr 06	5
29	To The Limit	WMV	100 MB	Maj. Spinelli	27 Apr 06	13
30	8	JPEG	259 KB	Maj. Spinelli	27 Apr 06	9
31	10	JPEG	264 KB	Maj. Spinelli	27 Apr 06	8
32	WEB KWingWorls	WMV	9.5 MB	Maj. Spinelli	27 Apr 06	10
33	11	JPEG	207 KB	Maj. Spinelli	27 Apr 06	6
34	Liquid2	MWV	126 MB	Maj. Spinelli	27 Apr 06	12
35	12	JPEG	184 KB	Maj. Spinelli	27 Apr 06	7
36	WEB KWingWorls	WMV	9.5 MB	Maj. Spinelli	27 Apr 06	11

Table D-7: Flight Profile 2 Aspect Investigation Data Ranges

Run Number	Antenna Hdg	Altitude	1Mbps (nm)	Start Run (Z)	End Run (Z)
1	0	12700	17.7	15:44:44	15:49:39
2	11.5	12750	14.6	15:52:31	15:58:17
3	23	12800	16.5	16:07:07	16:12:15
4	34.5	12720	15	16:15:15	16:20:41
5	45	12780	15.6	16:22:37	16:27:47
6	55.5	12800	16.4	16:30:55	16:35:41
7	68	12800	17.9	16:38:10	16:44:02
8	79.5	12800	17.1	16:46:47	16:52:11
9	90	12790	13.5	16:55:55	16:59:31
10	101.5	12780	16.8	17:02:51	17:08:00
11	113	12780	12.8	17:11:30	17:15:03
12	124.5	12780	16.5	17:18:10	17:22:48
13	135	12800	16.9	17:26:30	17:31:02
14	146.5	12800	16.2	17:33:00	17:38:15

Table D-7: Flight Profile 2 Aspect Investigation Data Ranges Continued

Run Number	Antenna Hdg	Altitude	1Mbps (nm)	Start Run (Z)	End Run (Z)
15	158	12820	13.4	17:41:35	17:45:19
16	169.5	12810	16.3	17:48:27	17:53:15

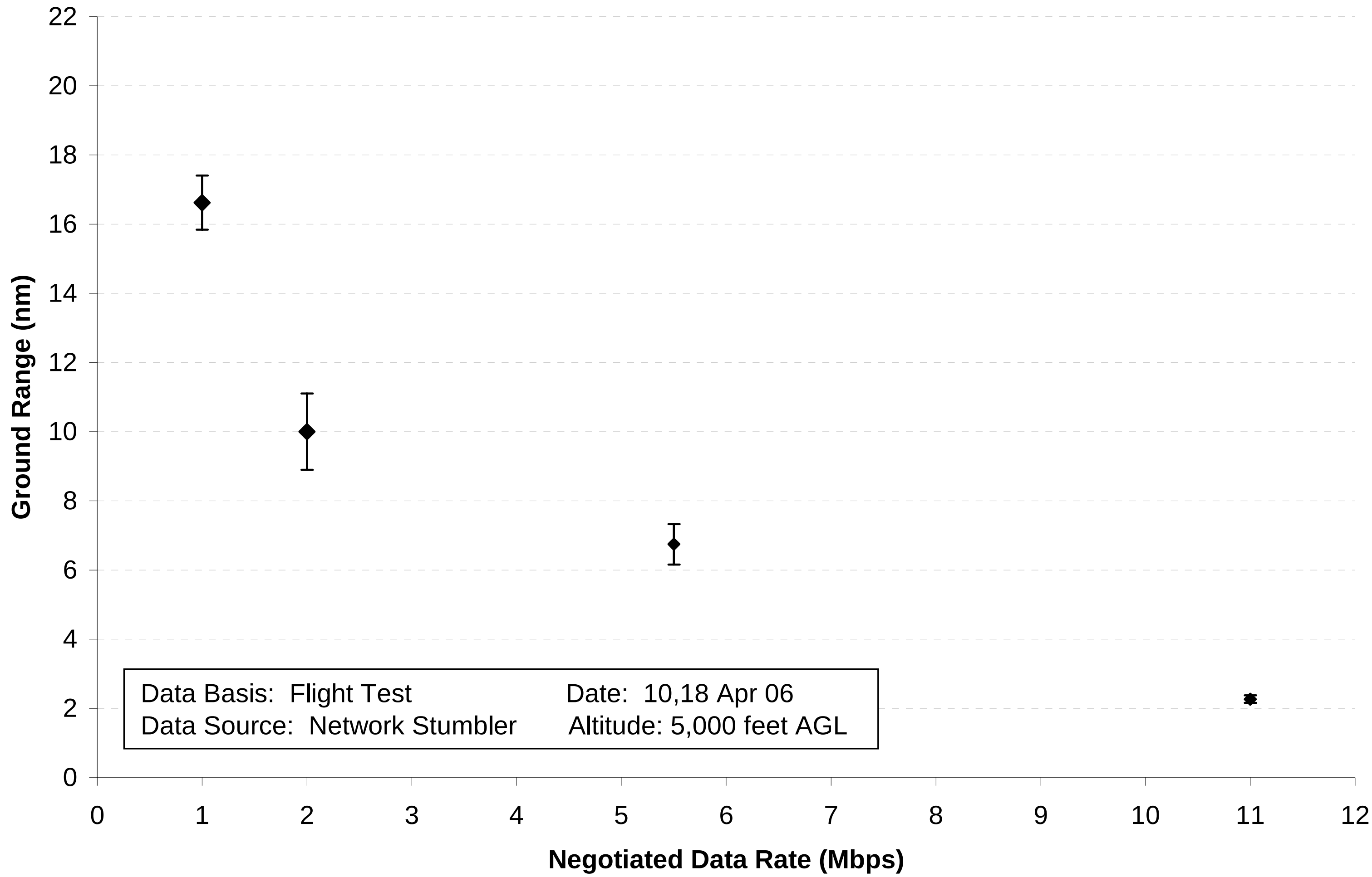

Figure D-1: 95 Percent Confidence Interval for 5,000 feet AGL Data Range Runs

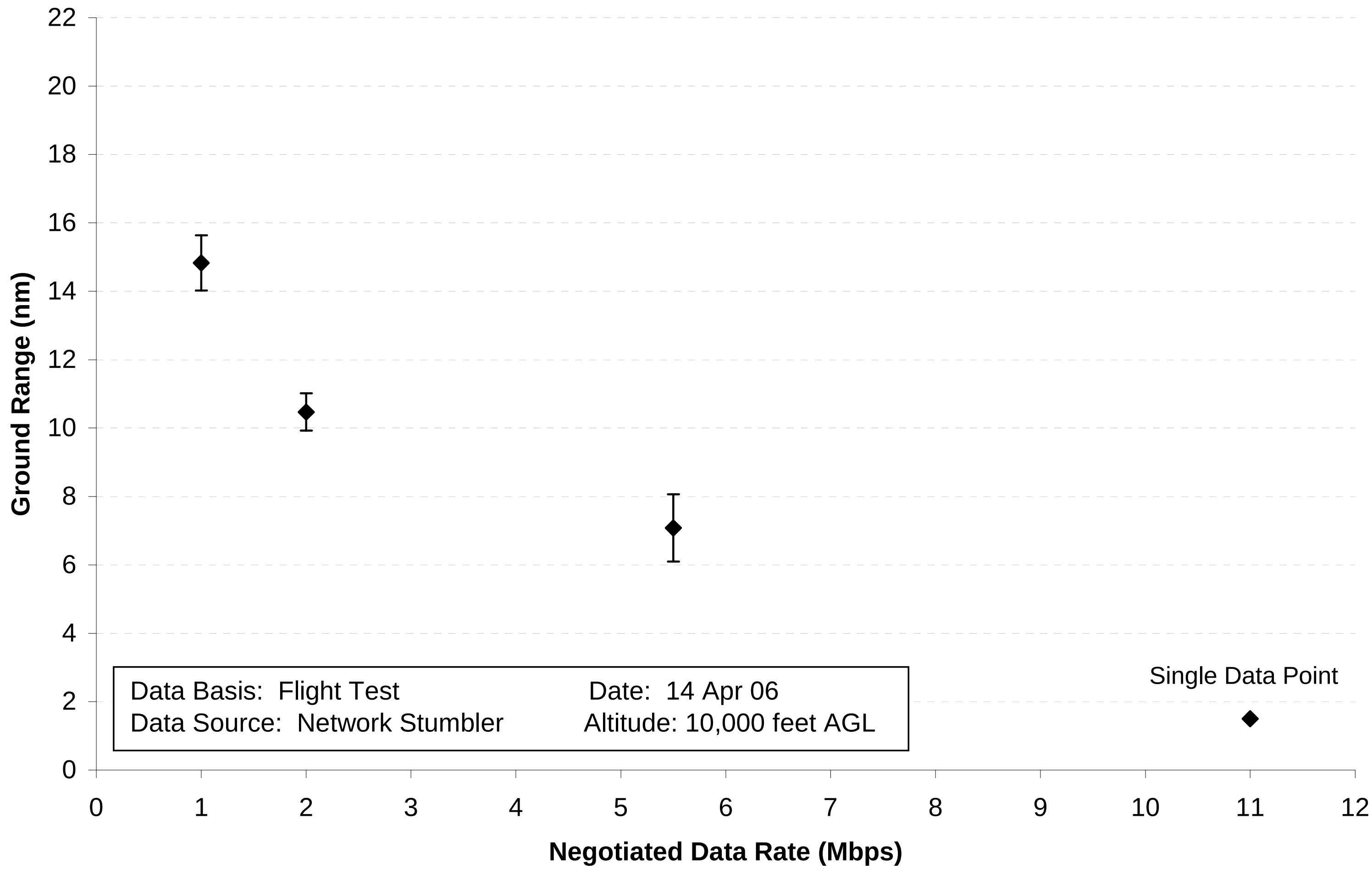

Figure D-2: 95 Percent Confidence Interval for 10,000 feet AGL Data Range Runs

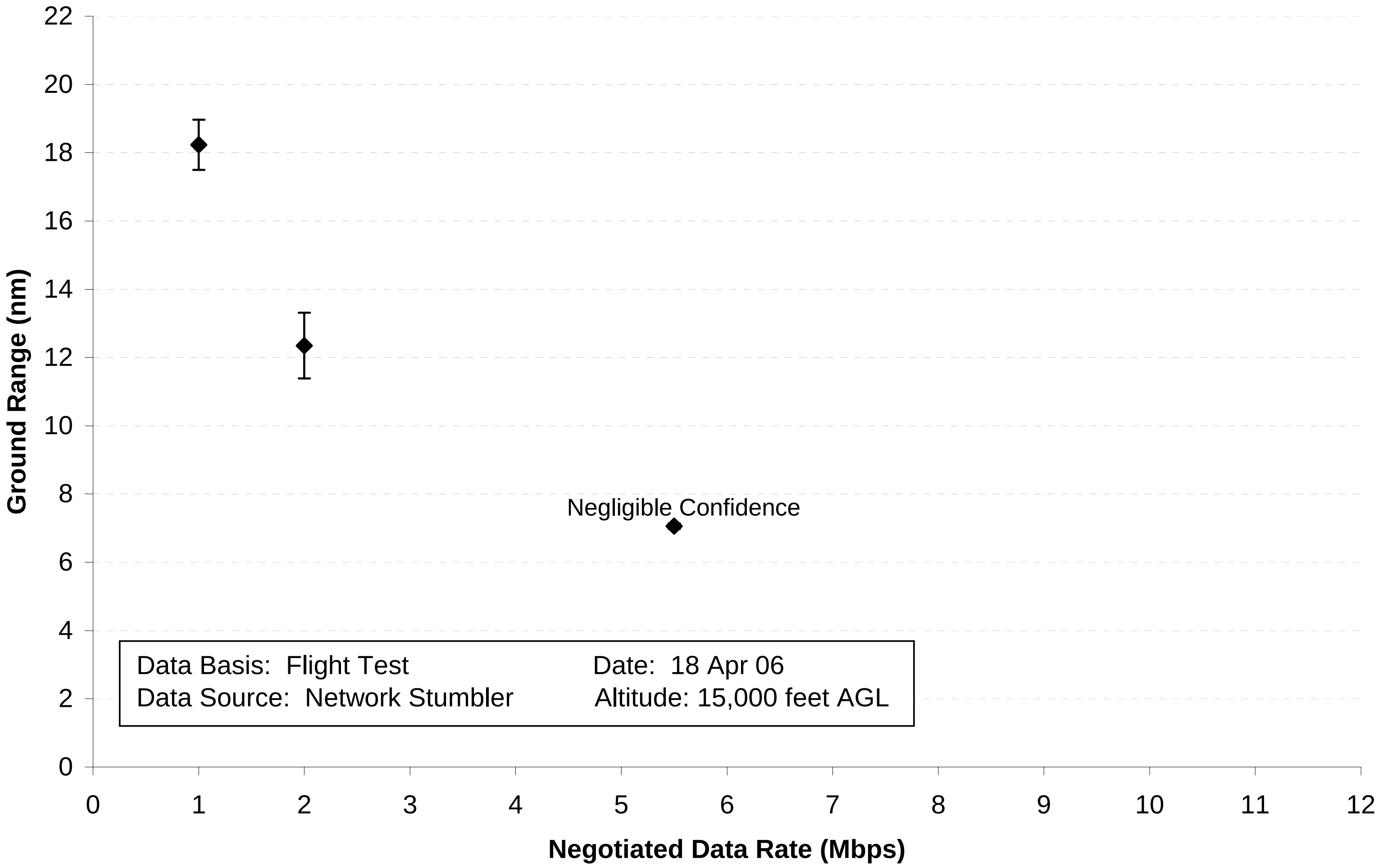

Figure D-3: 95 Percent Confidence Interval for 15,000 feet AGL Data Range Runs

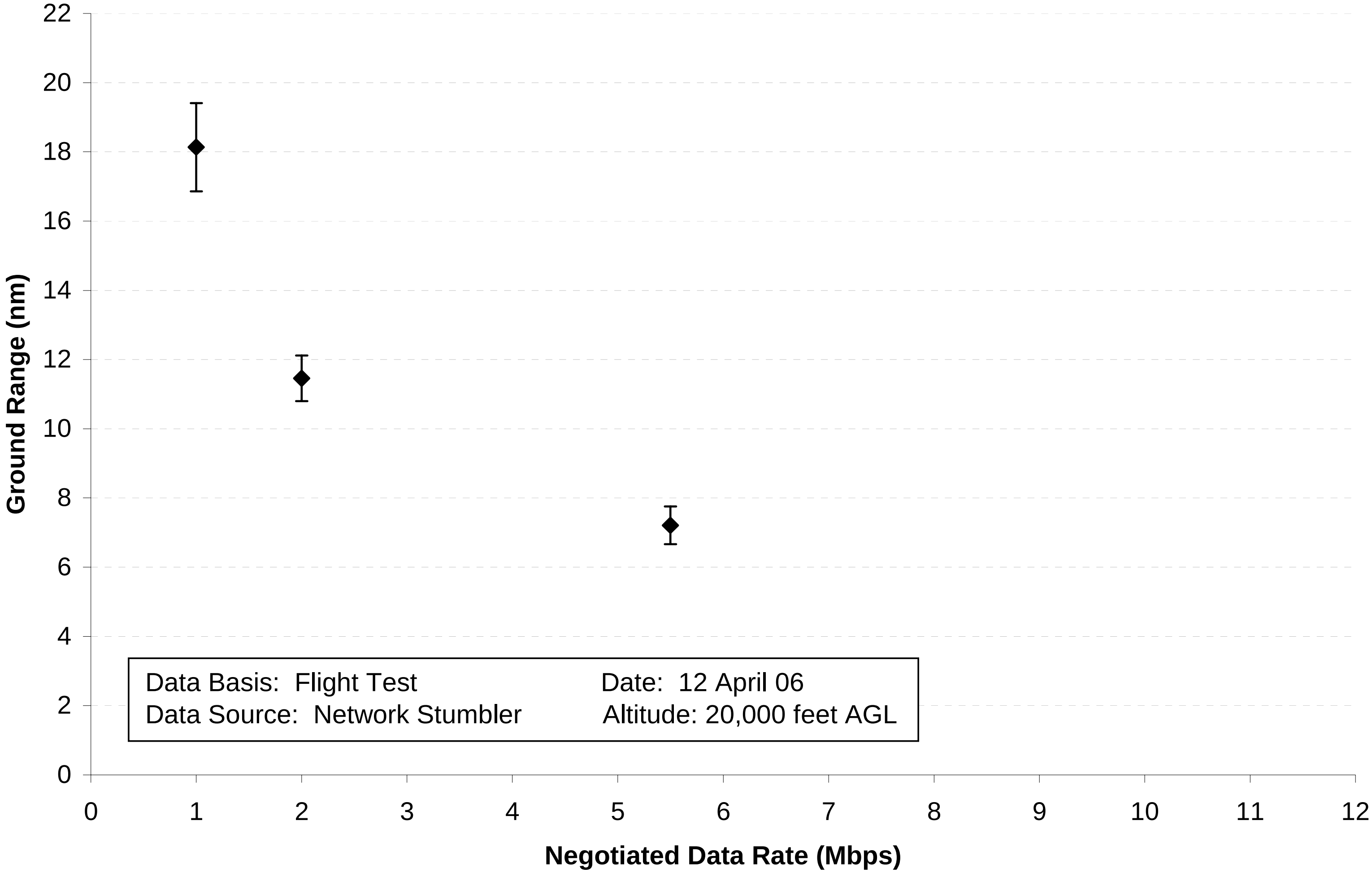

Figure D-4: 95 Percent Confidence Interval for 20,000 feet AGL Data Range Runs

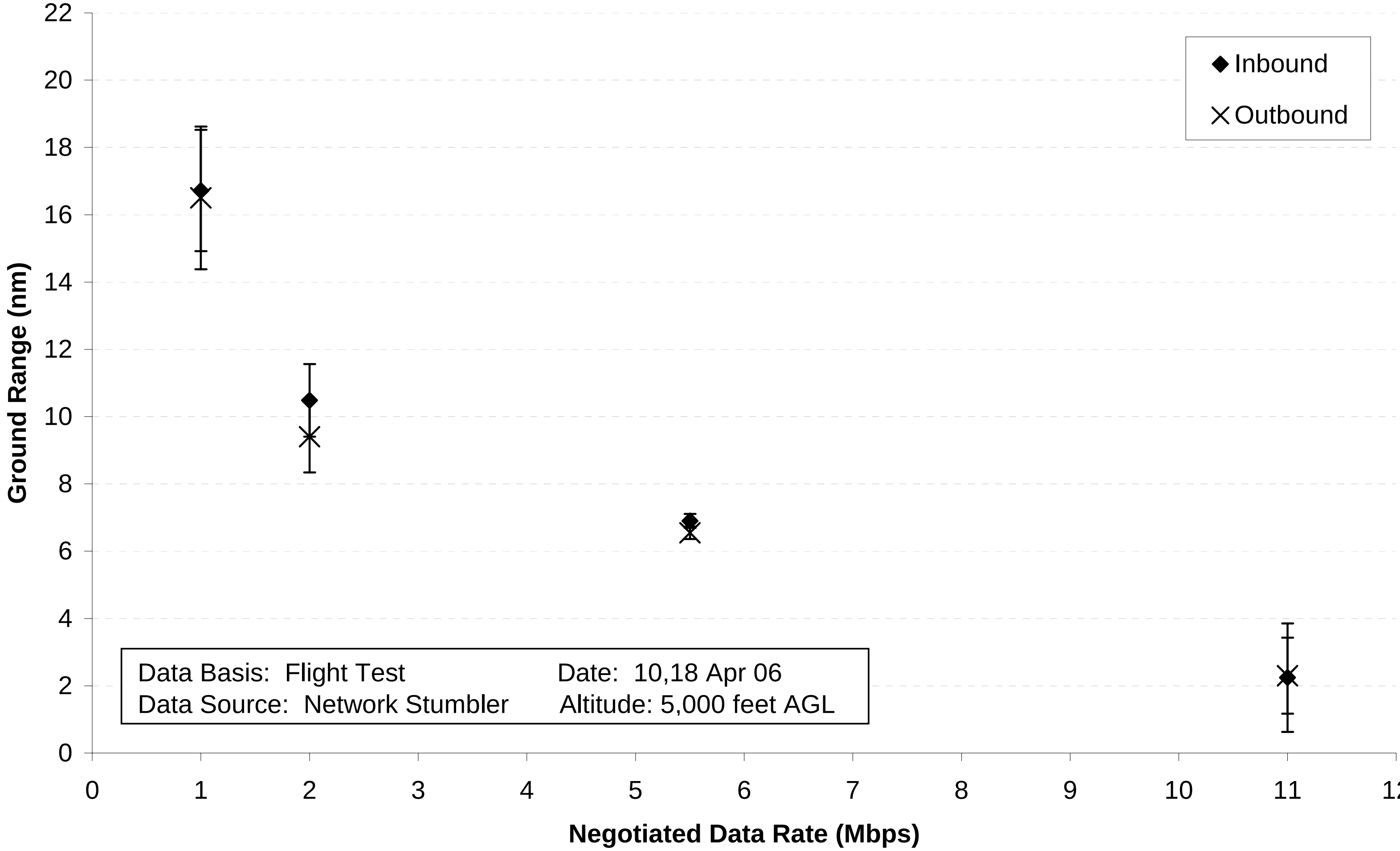

Figure D-5: Comparison of Inbound and Outbound Runs for 5,000 feet AGL with 95 Percent Confidence Interval

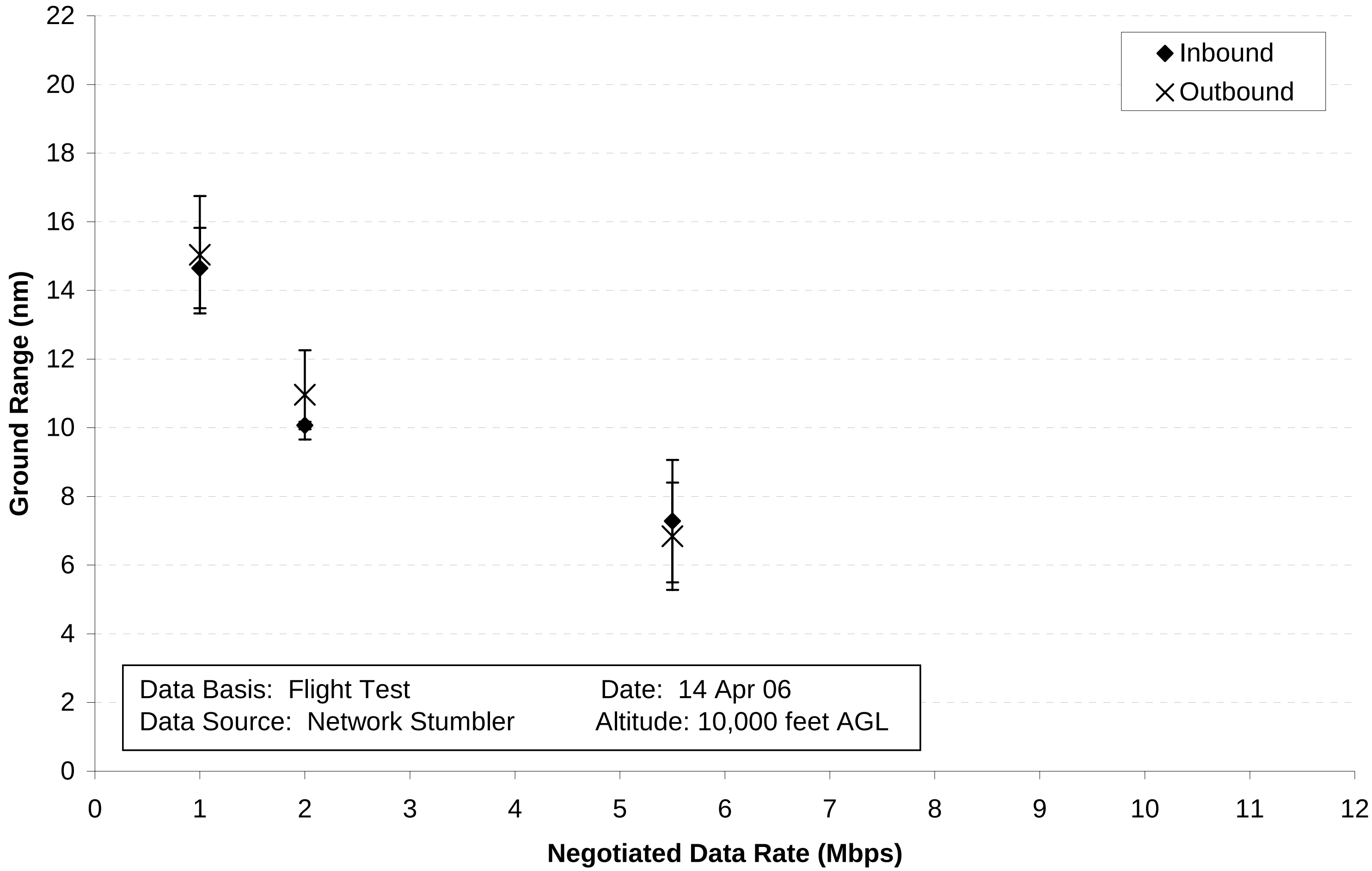

Figure D-6: Comparison of Inbound and Outbound Runs for 10,000 feet AGL with 95 Percent Confidence Interval

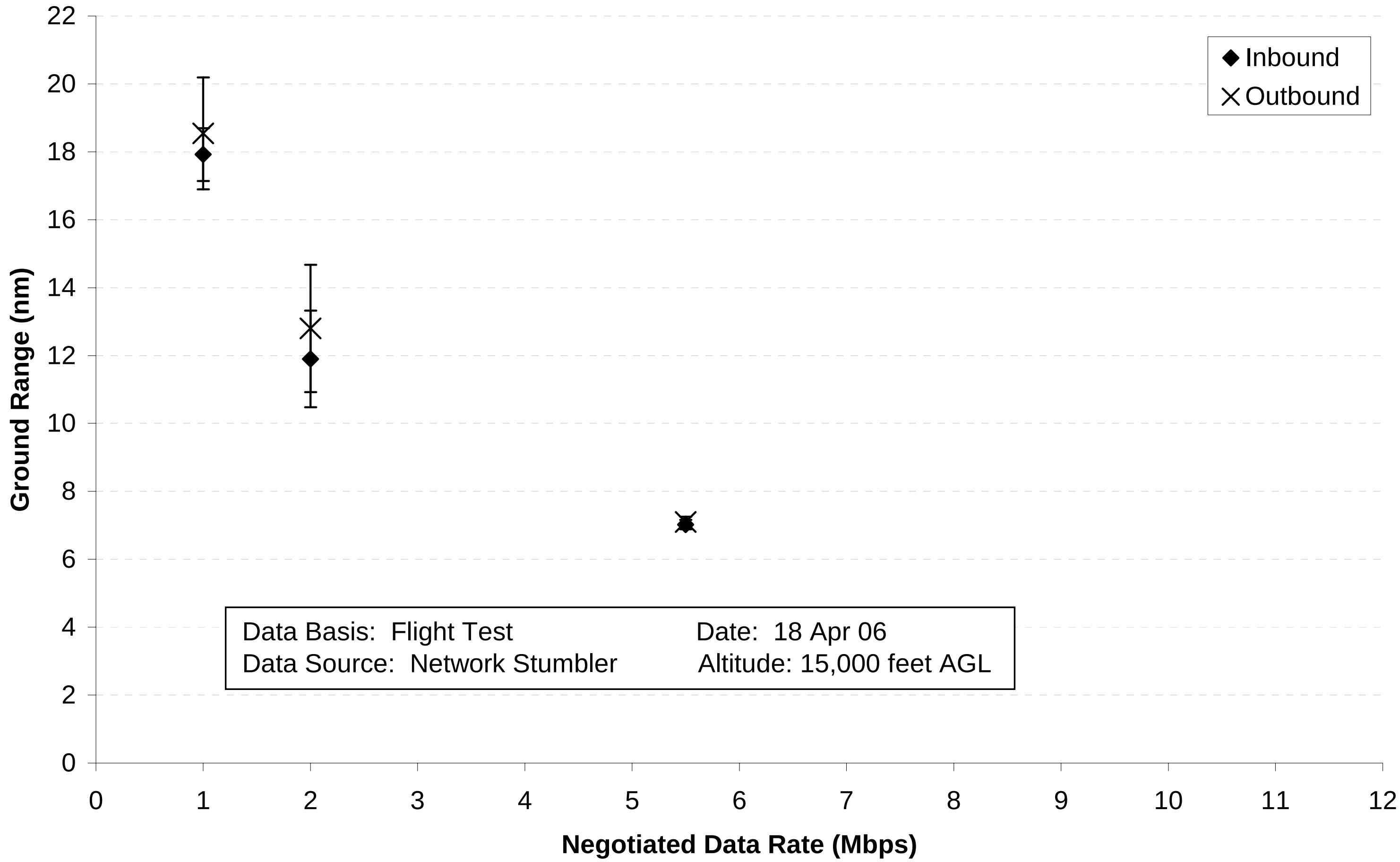

Figure D-7: Comparison of Inbound and Outbound Runs for 15,000 feet AGL with 95 Percent Confidence Interval

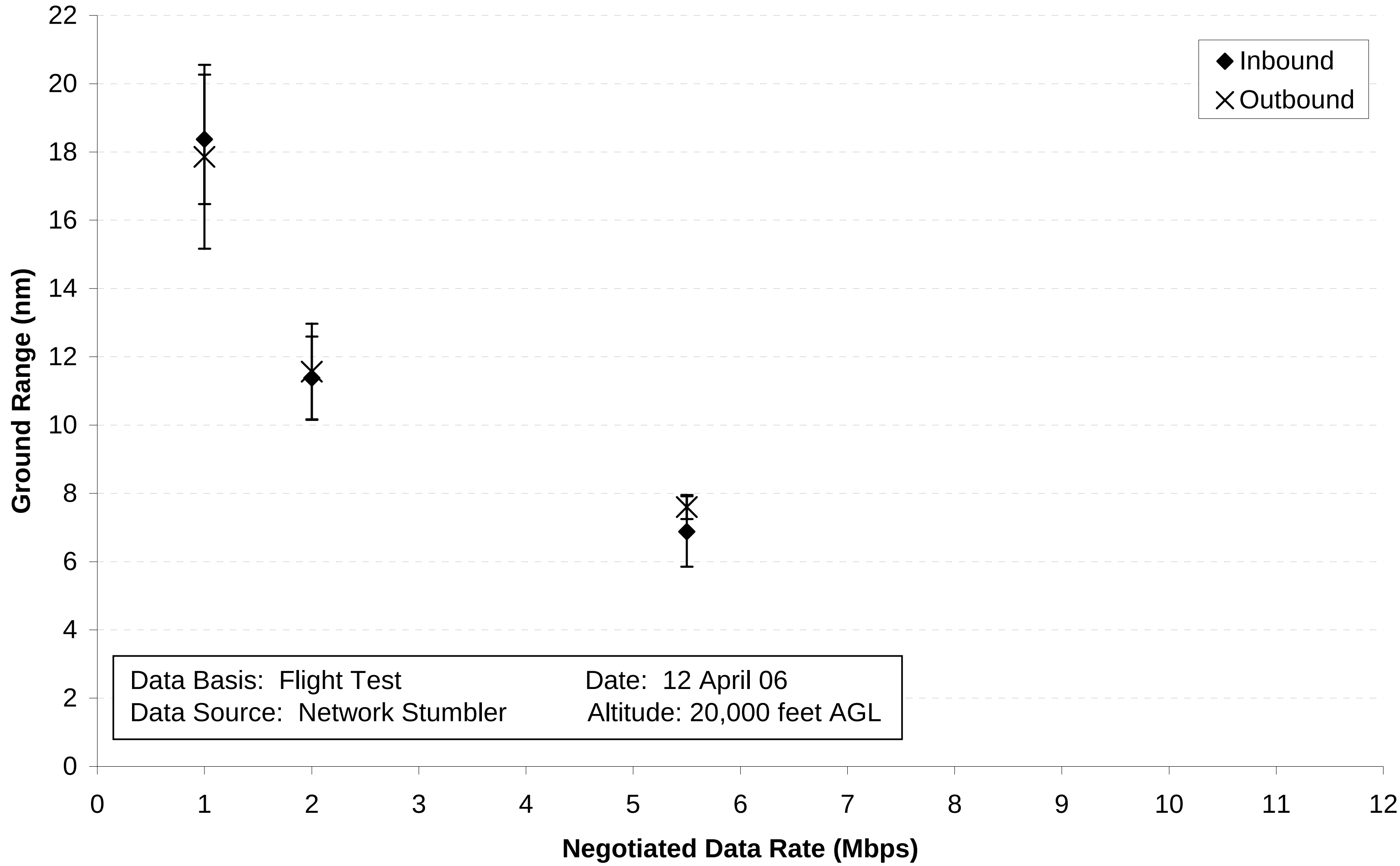

Figure D-8: Comparison of Inbound and Outbound Runs for 20,000 feet AGL with 95 Percent Confidence Interval

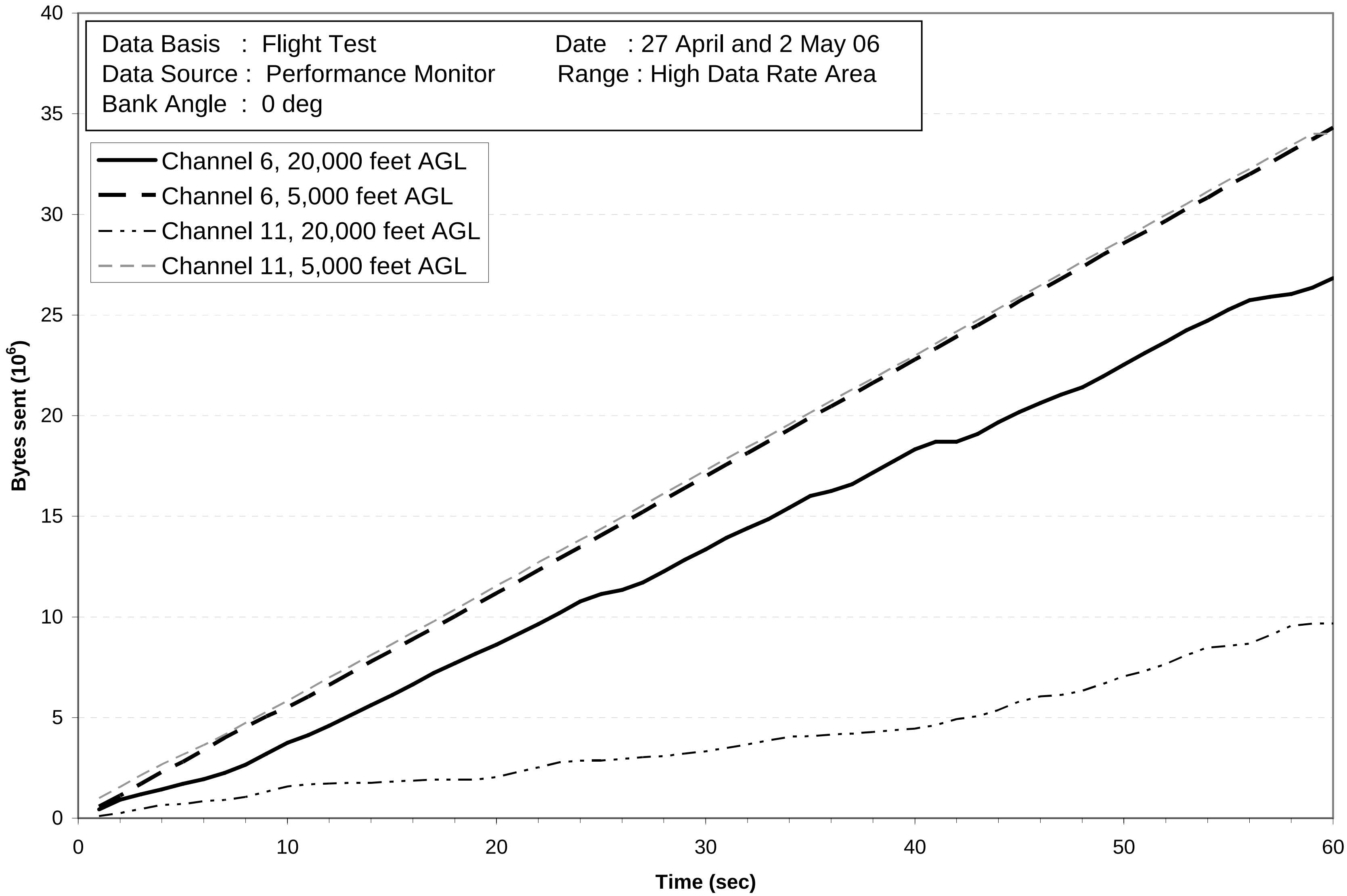

Figure D-9: Comparison of Altitude and Channel in the High Data Rate Connection Area

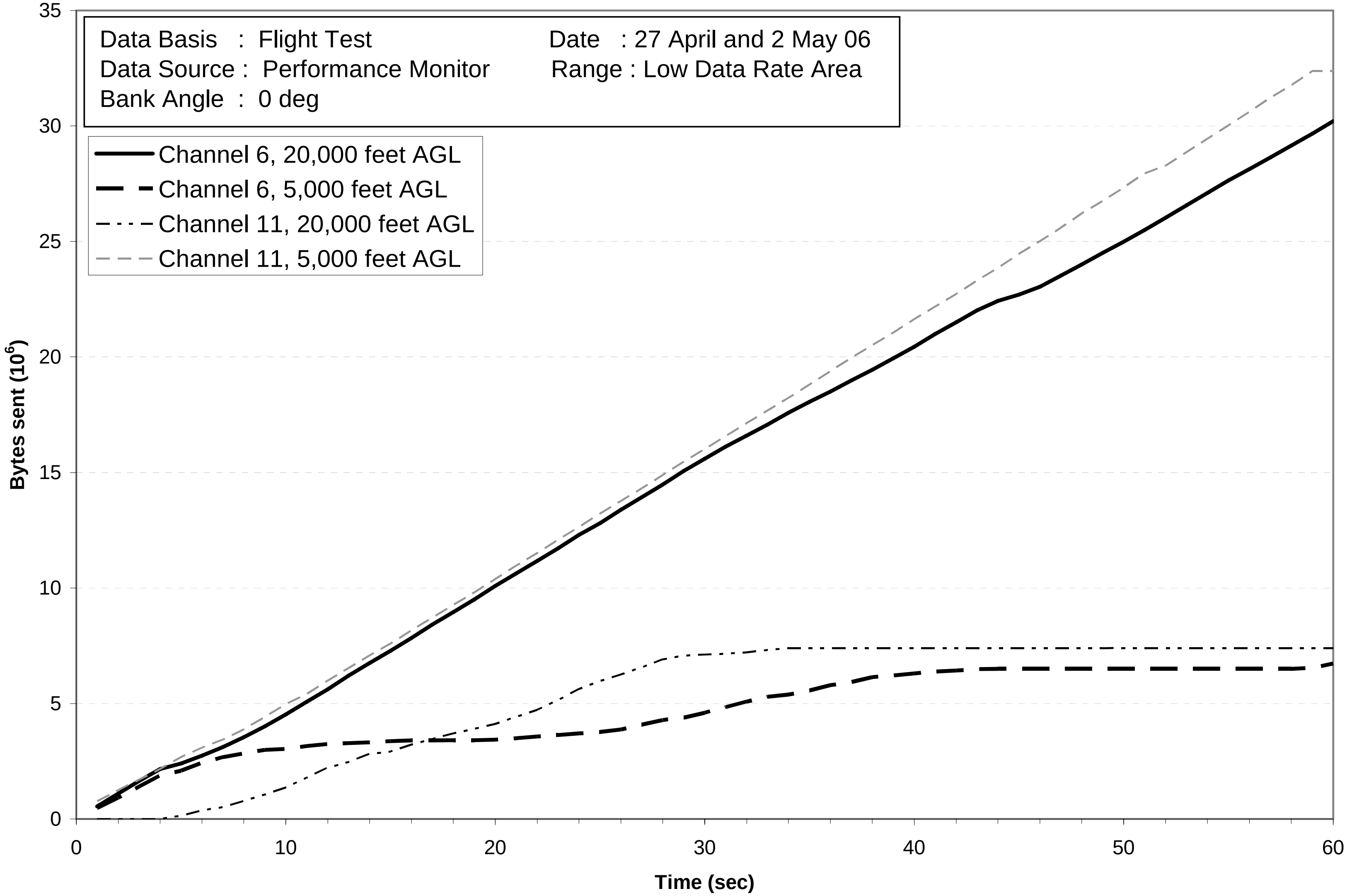

Figure D-10: Comparison of Altitude and Channel in the Low Data Rate Connection Area

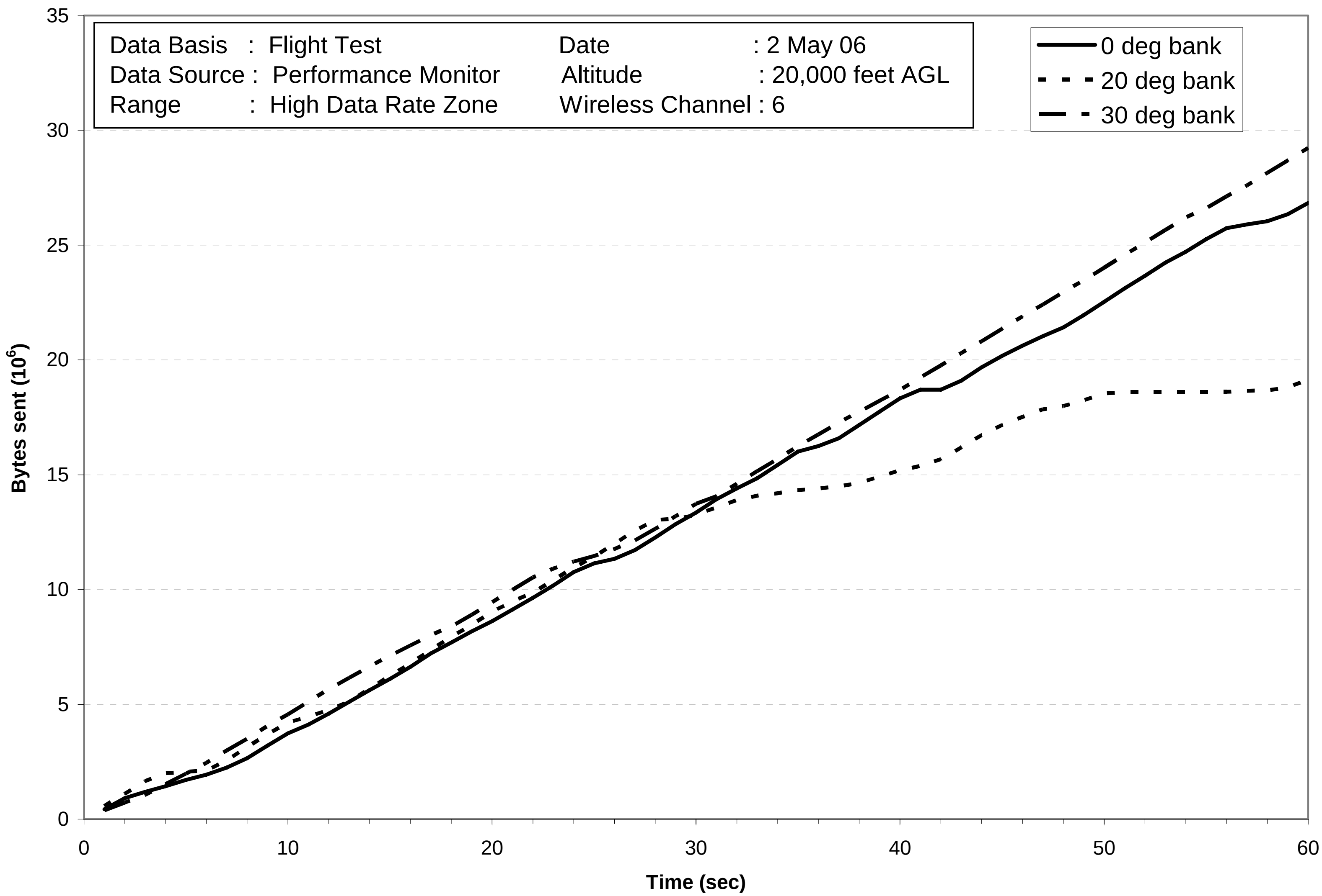

Figure D-11: Comparison of Banked Turns in the High Data Rate Connection Area at 20,000 feet AGL

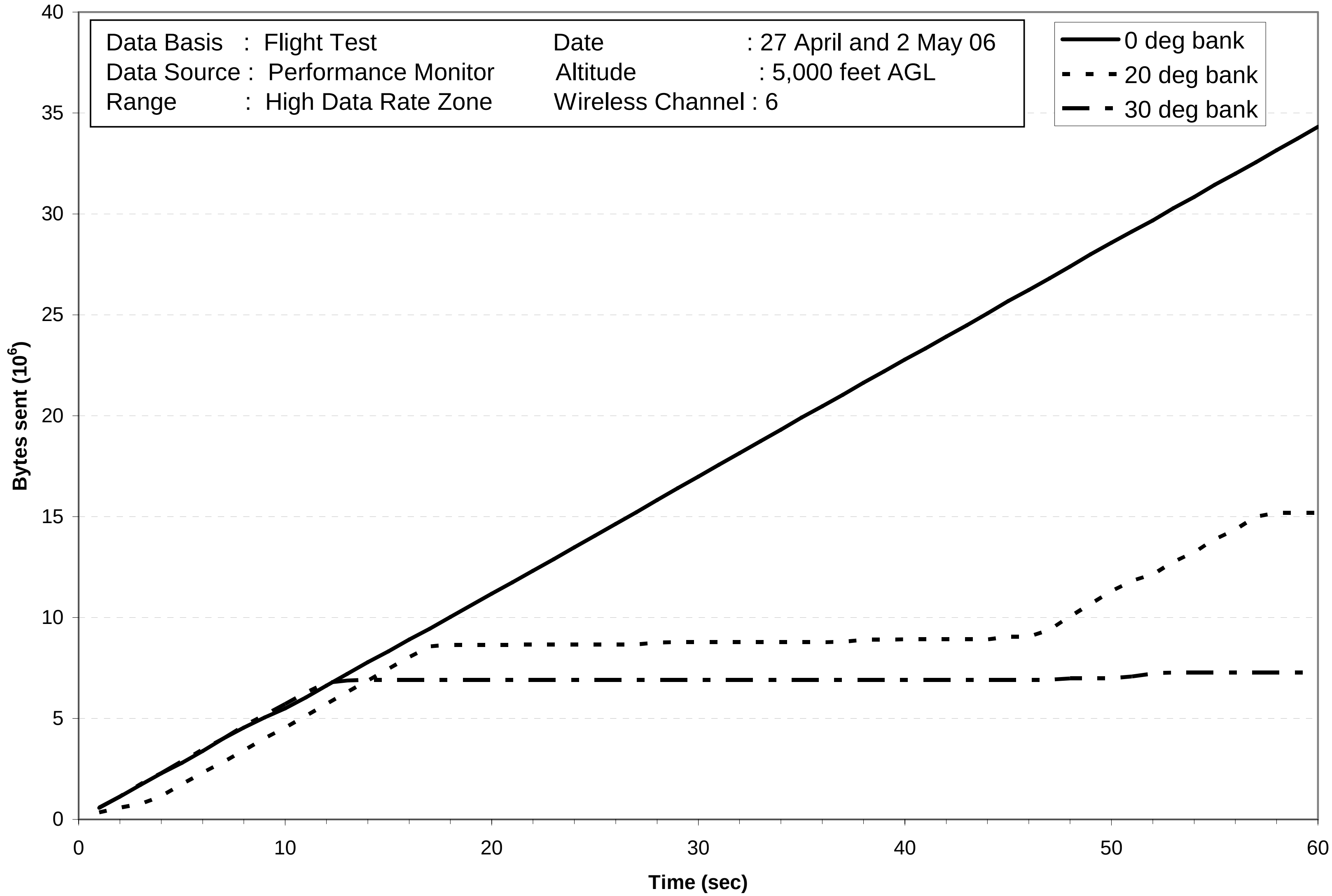

Figure D-12: Comparison of Banked Turns in the High Data Rate Connection Area at 5,000 feet AGL

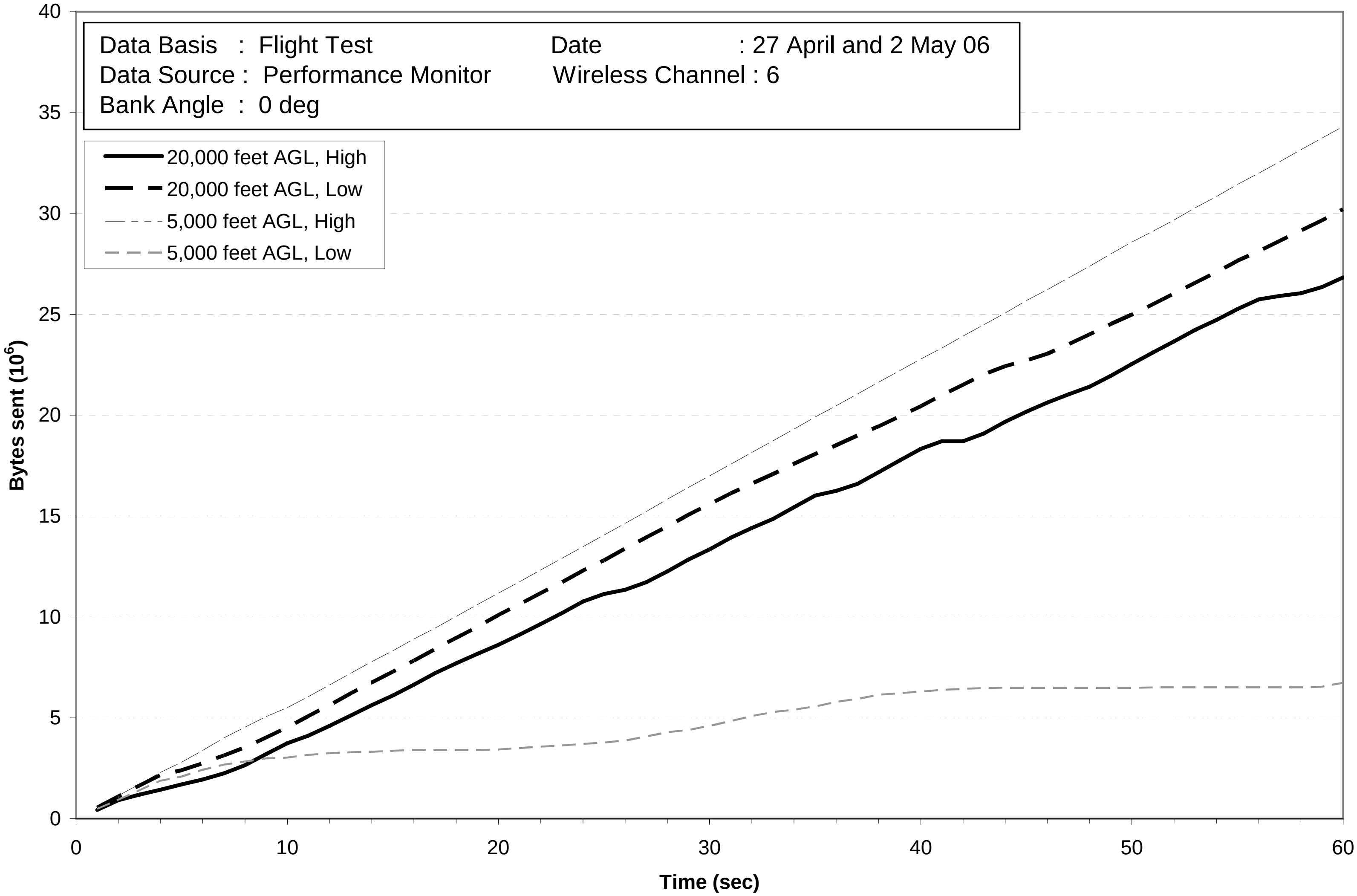

Figure D-13: Comparison of Data Throughput in Straight and Level Unaccelerated Flight

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APPENDIX E – LIST OF ACRONYMS

AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AGL	Above Ground Level
AVI	Audio Video Interleaved
CPU	Central Processing Unit
deg	Degrees
EGI	Embedded GPS/INS
EIRP	Effective Isotropic Radiated Power
GAINR	GPS Aided Inertial Reference
GHz	GigaHertz
GPS	Global Positioning System
INS	Inertial Navigation System
JPEG	Joint Photographic Experts Group
KIAS	Knots Indicated Airspeed
MBMS	Mission Battle Management System
Mbps	Megabits (10^6 bits) per second
MFD	Multi-Function Display
MPEG	Moving Picture Experts Group
MSL	Mean Sea Level
nm	Nautical Miles
PC	Personal Computer
PNF	Pilot Not Flying
RPM	Rotations Per Minute
SNR	Signal to Noise Ratio
SUT	System Under Test
TC	Test Conductor
TCP/IP	Transmission Control Protocol / Internet Protocol
TIM	Technical Information Memorandum

TMP	Test Management Project
TW	Test Wing
WMV	Windows Media Video

APPENDIX F – LESSONS LEARNED

MODIFICATIONS –

Although the modification occurred on time, there were problems during the initial coordination phase which could have led to delays later. The modification point of contact spent many hours coordinating between various agencies to get the proper information passed to the correct individuals.

- **LL: Connecting the right people together early in the modification process can prevent delays and reduce workload on the test team.**

The contractor provided and initial hardware schematic for the aircraft and ground stations which the test team modified to reflect the actual configuration. This schematic proved invaluable during tabletop discussions in the both the TPWG and Training Review Board/Safety Review Board to reduce confusion and facilitate learning.

- **LL: Have a detailed hardware schematic for any modifications to include ground and aircraft equipment.**

GROUND TESTING –

Hardware was brought by Lockheed-Martin to support the ground tests and preparation for first flight. This allowed the test team to work out configuration and compatibility issues prior to flight test. However, it was not possible to schedule the entire test team to be in place during all ground testing. This led to a steepened learning curve, as test team members often ended up with pieces of knowledge or experience with the system that were not integrated with the body of system familiarity. Ground testing and coordination with contractor support was beneficial to flight testing, but would have been better had the entire test team been available.

- **LL: Ensure all test team members are available throughout the ground test phase of the test program.**

AEROSPACE GROUND EQUIPMENT –

Aircraft ground power was readily available throughout ground testing. This allowed the test team to fully operate the system under test before using valuable flight hours, and it allowed the team to efficiently proceed with flight testing. The test team had coordinated with C-12C maintenance personnel in advance and was supported effectively throughout ground testing.

- **LL: Conduct as much preflight checkout on the ground using ground power as is practical.**

FLIGHT TESTING –

An issue recognized early in the program was the limit of electrical power available from the aircraft's generators. This could be improved by using equipment with a lower current draw, thereby creating a lower demand on the aircraft's electrical system, or increasing the power output of the generators.

- **LL: More electrical power on the aircraft is required to run network equipment, which consisted of multiple PCs, displays, and radio equipment/amplifiers.**

Interference was a factor throughout the test that could not be isolated due both to the open nature of the frequencies in the test and to the proximity to the test area of communities using wireless technology. Also, due to the frequency in which the equipment was designed to operate, it was subject to interference from sources other than wireless networks, including microwave ovens, telemetry stations, and wireless telephone handsets (cordless phones used on traditional telephone lines). Interference effects could be mitigated by performing testing in a remote area free of such sources, e.g. Nellis Air Force Range, Utah Test and Training Range, or over the Pacific Ocean.

- **LL: Test in an area free of interference sources.**

ON-SITE SYSTEM EXPERTISE –

Since this test was performed over publicly-available frequencies, the test team needed to contend with other transmission sources on those frequencies. In addition to moving the test to a remote geographical location, the test could be performed on a military-only frequency, or a frequency that requires special access or an amateur radio operator license. The frequency management expertise at Edwards AFB advised our team that use of such frequencies would require up to 2 years of advance coordination. This will need to be considered for future test programs of this type.

- **LL: Frequency spectrum coordination requires 18 months to 2 years of lead time.**

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